

FINAL DESIGN PACKAGE FOR
THE FS - 12 PRODUCT RECOVERY SYSTEM

VOLUME II
DESIGN CALCULATIONS

MASSACHUSETTS MILITARY RESERVATION
CAPE COD, MASSACHUSETTS

JULY, 1994



INSTALLATION RESTORATION PROGRAM

**FINAL DESIGN PACKAGE FOR
THE FS-12 PRODUCT RECOVERY SYSTEM**

**VOLUME II
DESIGN CALCULATIONS**

**MASSACHUSETTS MILITARY RESERVATION
CAPE COD, MASSACHUSETTS**

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JULY 1994

SOIL VAPOR EXTRACTION/AIR SPARGING
CALCULATIONS

INDEX

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Extent of Soil Contamination

The extent of contamination shown in Figure 1 was estimated by a qualitative evaluation of organic vapor concentrations in samples of soil taken during well drilling. Samples were taken at several depths, typically at 5-foot intervals between 70 and 90 feet bgl, and stored in closed containers. Each container was later opened, and the concentration of volatile organics in the container headspace was measured with an organic vapor meter. As expected, concentrations in soil taken from wells near the spill site⁽¹⁾ were relatively high, typically 200 ppmv. As the distance from the spill site increased, concentrations generally decreased and eventually became zero. (Typical examples are listed in Table 1.) In this manner, the boundary of the contaminated soil area was estimated. The profile (elliptical, with the major axis elongated downgradient) is typical of a plume from a single source, dispersing in a relatively uniform medium. The actual area expected to be affected by soil venting overlaps the estimated area, as shown in Figure 2.

(1)

The location of the spill site is near the north shoulder of Greenway Road, where it intersects the west leg of the "unpaved road" loop.

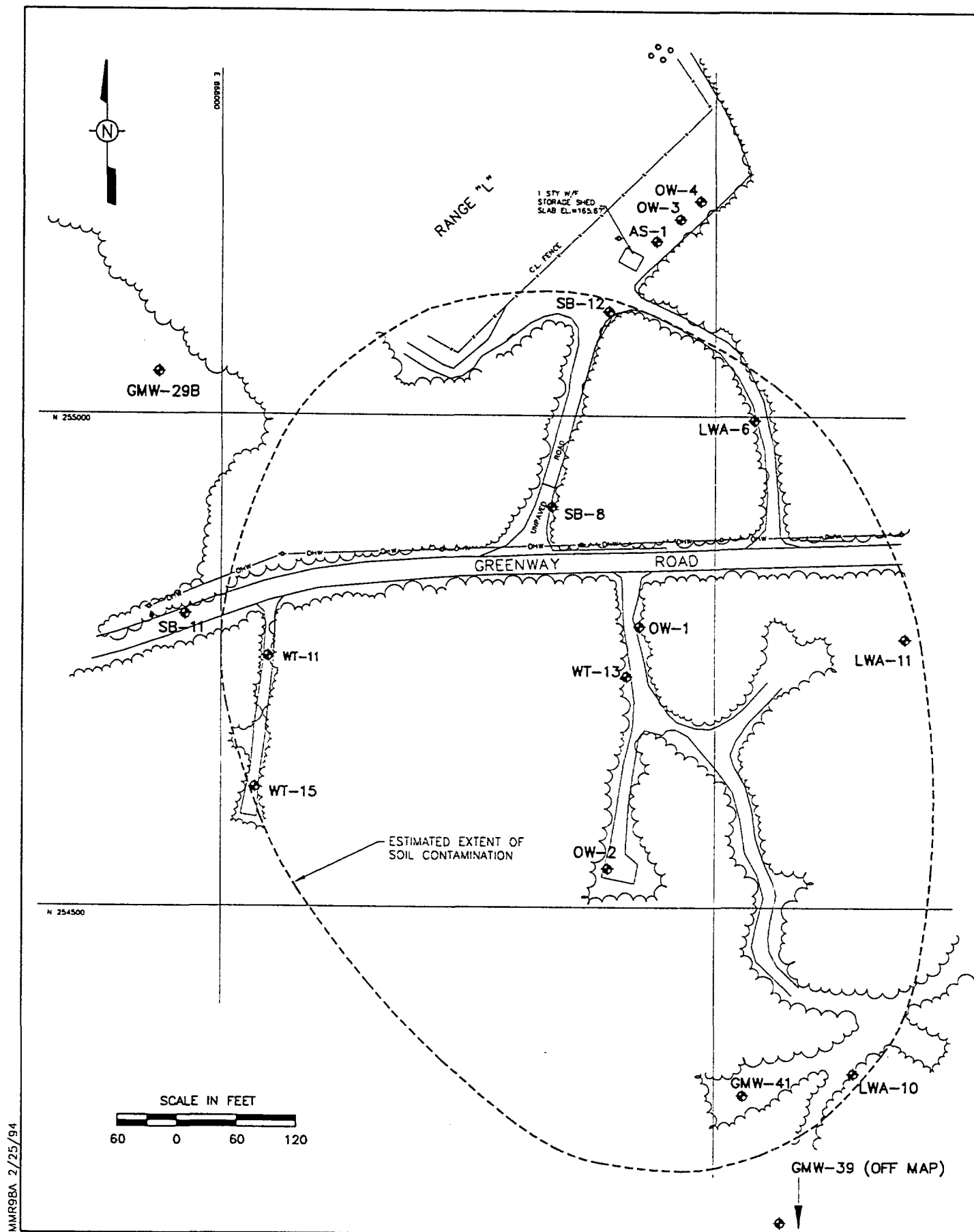


FIGURE 1. SOIL CONTAMINATION

Table 1: Headspace Concentrations of Volatile Organics

Well Number	Headspace Concentration (ppmv)	Comment
SB-8	> 250	(Typical examples of relatively high concentrations in soils from wells near the location of the spill.)
OW-1	> 200	
WT-13	> 200	
OW-2	> 200	
OW-3	0	(Examples of relatively low concentrations in soils from wells near the periphery of the "estimated extent of soil contamination" shown in Figure 1.)
OW-4	0	
AS-1	0	
SB-12	≈ 50	
LWA-6	0	
LWA-11	≈ 50	
LWA-10	≈ 90	
GMW-41	0	
GMW-39	0	
WT-15	< 50	
WT-11	≈ 100	
SB-11	< 50	
GMW-29B	0	

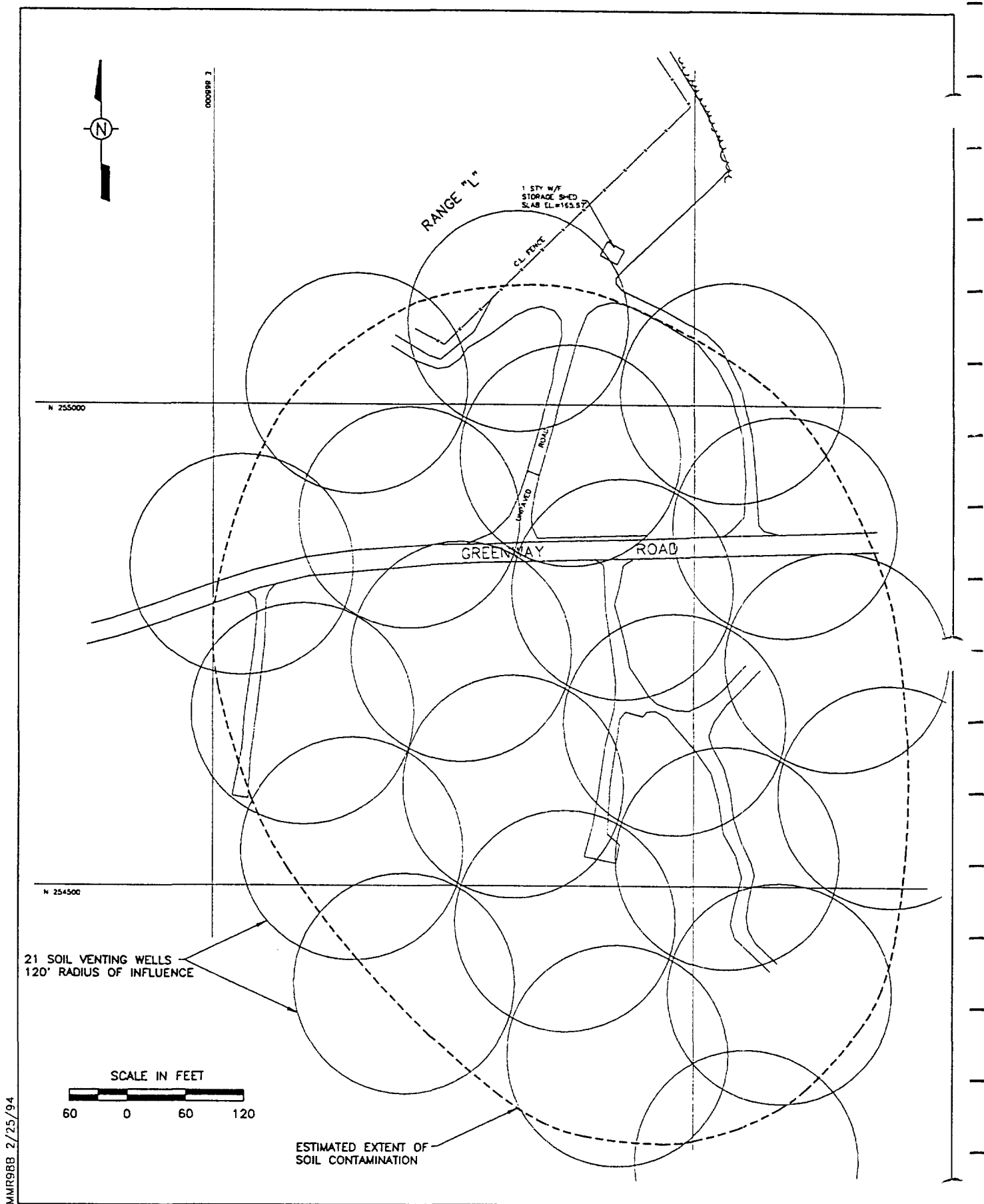


FIGURE 2. AFFECTED AREA OF SOIL VENTING

SECTION 1

Extent of Contamination at the FS-12 Site

SECTION 2

**HYPERVENTILATE Results and Air Permeability Results for 150 and
180 CFM**

IS VENTING APPROPRIATE?

"Is Venting Appropriate" card in the HyperVentilate program was used to estimate constituent vapor pressure, vapor concentration and the maximum removal rate. Since the free product identified at MMR was judged to be aged JP-4, the HyperVentilate program data-base-defined 62 chemical compositions of gasoline and the vapor pressures were used for this estimation. The method of estimating vapor concentration was described in Johnson et al., 1990a. The equilibrium or saturated vapor concentration is the maximum vapor concentration of any mixture of volatile constituents in extracted vapors. This concentration was calculated based on the molecular weight and vapor pressure at the soil temperature for each constituent in the contaminant mixture, the residual soil contaminant composition, and the ideal gas law. The software adjusts the vapor pressure and concentration estimates to allow for soil temperature changes. The calculation of estimated maximum removal rates is a function of the maximum vapor concentration and the estimated vapor flow rate. Then the preliminary assessment of SVE feasibility can be done by comparing the desired removal rate and the estimated range of removal rate.

The three main factors that govern the success of a venting operation are:

- vapor flow rate
- vapor concentrations
- subsurface stratigraphy (the location of contaminants relative to the vapor flow path)

After the average estimated air permeability was determined, the flow rate with the designed well vacuum can be estimated by the "HyperVentilate" program. The estimated air permeability was in the range of 142-584 darcy with an average of 305 darcy. A conservative range of 270-305 darcy was selected for this estimate, the other parameters used were well radius of 2 inches, radius of influence of 120 feet, interval thickness of 20 feet, and the well vacuum of 3 inches of water. The range of flow rate was estimated to be 135.95-153.57 SCFM. The flow rate estimation is presented in figure VE-1. For weathered gasoline at soil temperature of 10 °, the calculated vapor pressure is 0.04077 atm and the calculated vapor concentration is 142.71 mg/l. The vapor concentration estimation is presented in figure VE-2. The compound list with molecular weight and vapor pressure at 10 °C is presented in figure VE-3.

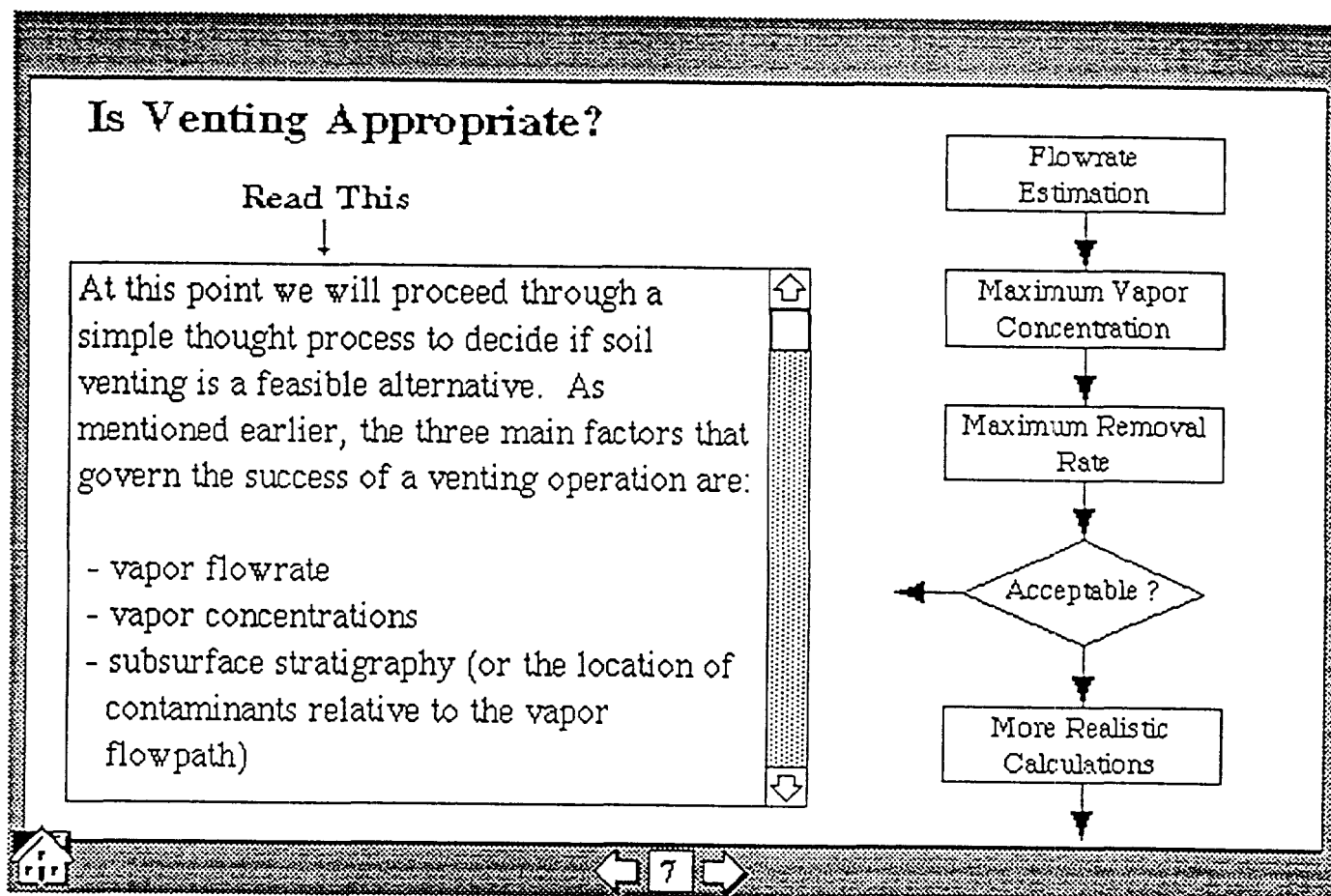
The saturated vapor concentration at time zero and the minimum volume to remove >90% of initial residual were estimated to be 147.7 mg/l and 221.25 l/g. The vapor concentration and critical volume estimation is presented in figure VE-4. The maximum achievable removal rate is simply the product of the flow rate times the "saturated" vapor concentration. The removal rate estimation is presented in figure VE-5.

Again, is soil venting appropriate? We compared the maximum possible removal rate with the desired removal rate. The desired removal rate was obtained by dividing the estimated spill mass of 186220 kg by the desired remediation time of 730 days and that is 255 kg/day. The desired removal rate was much less than the estimated achievable removal rate of 797.28-900.56 kg/day. Also, we evaluated the relative efficiency which was the ratio of the predicted removal rate to the removal rate that would be obtained if the extracted vapors were saturated, or in equilibrium with the liquid phase. The relative efficiency was in the range of 30.2-32% which was practically acceptable to make SVE an appropriate remediation alternative for MMR. The final determination of "Is soil venting appropriate?" is presented in figure VE-6.

SYSTEM DESIGN

After the conclusion was made that the use of SVE with the preliminary design parameters such as well vacuum, well size, removal rate etc., was an appropriate remedial option, HyperVetilate was used to estimate the minimum wells required for the SVE system. The design parameters input were medium sand, screened interval of 20 ft, radius of contaminated zone of 391 ft, average concentration of 342 mg/kg, calculated total mass of 158064 kg, air permeability at 270-305 darcy, design well vacuum at 3 inches of water, well radius of 2 inches, radius of influence of 120 ft, critical volume of air at 221.25 l/g, at 25% removal efficiency, time for clean-up of 730 days, expected flow rate at 135.9-153.5 SCFM. The software estimated minimum number of wells were 10.6 wells based on area and 30.4-34.3 wells based on critical volume. These results were then used as reference for the SVE system design. The software aid system design is presented in figure VE-7.

Figure VE-1. Flow rate estimation.



Flowrate Estimation:

☐ Medium Sand
☐ Fine Sand
☐ Silty Sand
☐ Clayey Silts
☒ Input Your Own Permeability Range

Permeability Range

to

Well Radius in

Radius of Influence ft

Interval Thickness* ft

--> Calculate Flowrate Ranges<--

1) Choose Soil Type, or
Optional - Enter your own permeability values (darcy)

2) Enter Well Radius (in)

3) Enter Radius of Influence (ft) & Interval Thickness*

4) Optional - Enter your own well vacuum (406" = max)

5) Click button to calculate Predicted Flowrate Ranges

Predicted Flowrate Ranges

Well Vacuum P_w (in H_2O)	Flowrate (SCFM) (single well)	
5	226.03	to 255.33
10	449.26	to 507.49
20	887.33	to 1002.36
40	1729.94	to 1954.19
60	2527.82	to 2855.50
120	4653.12	to 5256.30
<input type="text" value="3"/>	135.95	to 153.57

* thickness of screened interval, or permeable zone (whichever is smaller).

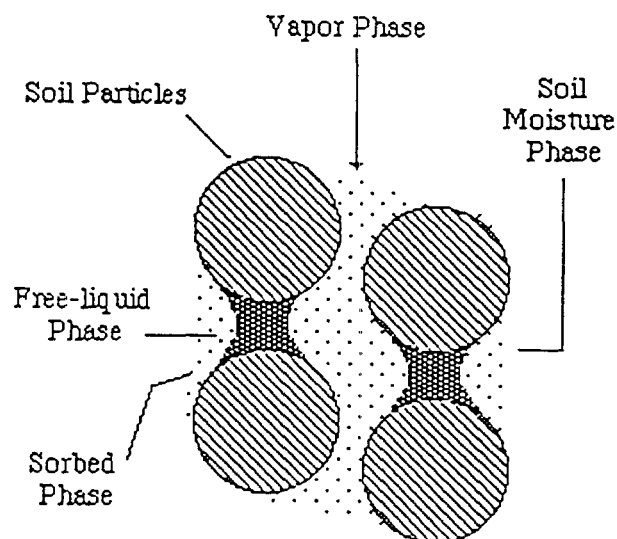
About Soils (& Unit Conversions)
8
Info about Calculation

Figure VE-2. The vapor concentration estimation.

Vapor Concentration Estimation:

The maximum achievable removal rate occurs whenever the vapors removed by venting are "saturated" or in equilibrium with the contaminant/soil matrix.

In the next card you will estimate the maximum vapor concentration of your contaminant. Just follow the instructions in the upper left corner of the next card.



Vapor Concentration Estimation - Calculation

- 1 Type in Temperature ($^{\circ}\text{C}$) (hit <return>) 10
- 2 Click to Enter Composition of Contaminant ☐ Enter Distribution
or ☐ "Fresh" Gasoline
Choose one of the Default Distributions ☒ "Weathered" Gasoline
- 3 Click to View Distributions, (optional) View Distributions
- 4 Click to Perform Calculations ☒ Perform Calculations

Results

Sum of Mass Fractions	1.00000	
Calc. Vapor Pressure	0.04077	atm
Calc. Vapor Concentration	142.70906	mg/l

Figure VE-3. The compound list with molecular weight and vapor pressure at 10 °C.

H16

Help: Compound List

'Weathered'
Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 10 °C	
1	propane	0.00	44.1	6.41294	↑
2	isobutane	0.00	58.1	2.14938	□
3	n-butane	0	58.1	1.49922	↓
4	trans-2-butene	0	56.1	1.39448	
5	cis-2-butene	0	56.1	1.25363	
6	3-methyl-1-butene	0	70.1	0.62819	
7	isopentane	0.0069	72.2	0.56058	
8	1-pentene	0.0005	70.1	0.47780	
9	2-methyl-1-butene	0.0008	70.1	0.45314	
10	2-methyl-1,3-butadiene	0.0000	68.1	0.46553	↓
		1.00000 = Sum of Mass Fractions (should be ≈1)			

How Do I Measure a Distribution?
Return to Vapor Conc. Estimation Card
Print Lists

H16

Help: Compound List

'Weathered'
Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 10 °C	
11	n-pentane	0.0095	72.2	0.38840	↑
12	trans-2-pentene	0.0017	70.1	0.34365	□
13	2-methyl-2-butene	0.0021	70.1	0.33809	↓
14	3-methyl-1,2-butadiene	0.001	68.1	0.30519	
15	3,3-dimethyl-1-butene	0	84.2	0.31539	
16	cyclopentane	0.0046	70.1	0.23475	
17	3-methyl-1-pentene	0	84.2	0.19041	
18	2,3-dimethylbutane	0.0044	86.2	0.17006	
19	2-methylpentane	0.0207	86.2	0.13269	
20	3-methylpentane	0.0186	86.2	0.12938	↓
		1.00000 = Sum of Mass Fractions (should be ≈1)			

How Do I Measure a Distribution?
Return to Vapor Conc. Estimation Card
Print Lists

Figure VE-3. The compound list with molecular weight and vapor pressure at 10 °C.

H16

Help: Compound List

'Weathered'
Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 10 °C	
21	n-hexane	0.0207	86.2	0.10182	↑
22	methylcyclopentane	0.0234	84.2	0.09615	
23	2,2-dimethylpentane	0.0064	100.2	0.06907	
24	benzene	0.0021	78.1	0.06196	
25	cyclohexane	0.0137	84.2	0.06236	
26	2,3-dimethylpentane	0.00	100.2	0.04446	
27	3-methylhexane	0.0355	100.2	0.03911	
28	3-ethylpentane	0.00	100.2	0.03665	
29	2,2,4-trimethylpentane	0.0503	114.2	0.03108	
30	n-heptane	0.0447	100.2	0.02742	↓

1.00000 = Sum of Mass Fractions
(should be ≈1)

How Do I Measure a Distribution?
Return to Vapor Conc. Estimation Card
Print Lists

H16

Help: Compound List

'Weathered'
Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 10 °C	
31	methylcyclohexane	0.0393	98.2	0.02925	↑
32	2,2-dimethylhexane	0.0207	114.2	0.02086	
33	toluene	0.0359	92.1	0.01711	
34	2,3,4-trimethylpentane	0	114.2	0.01664	
35	2-methylheptane	0.0324	114.2	0.01208	
36	3-methylheptane	0.0343	114.2	0.01137	
37	n-octane	0.030	114.2	0.00793	
38	2,4,4-trimethylhexane	0.0034	128.3	0.00744	
39	2,2-dimethylheptane	0.0226	128.3	0.00620	
40	ethylbenzene	0.013	106.2	0.00513	↓

1.00000 = Sum of Mass Fractions
(should be ≈1)

How Do I Measure a Distribution?
Return to Vapor Conc. Estimation Card
Print Lists

Figure VE-3. The compound list with molecular weight and vapor pressure at 10 °C.

H16

Help: Compound List

'Weathered'
Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 10 °C	
41	p-xylene	0.0151	106.2	0.00479	↑
42	m-xylene	0.0376	106.2	0.00443	
43	3,3,4-trimethylhexane	0.0056	128.3	0.00401	
44	o-xylene	0.0274	106.2	0.00363	
45	2,2,4-trimethylheptane	0.0012	142.3	0.00289	
46	n-nonane	0.0382	128.3	0.00225	
47	3,3,5-trimethylheptane	0.0000	142.3	0.00198	
48	n-propylbenzene	0.0117	120.2	0.00176	
49	2,3,4-trimethylheptane	0	142.3	0.00165	
50	1,3,5-trimethylbenzene	0.0493	120.2	0.00126	↓

1.00000 = Sum of Mass Fractions (should be =1)

How Do I Measure a Distribution?
Return to Vapor Conc. Estimation Card
Print Lists

H16

Help: Compound List

'Weathered'
Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 10 °C	
51	1,2,4-trimethylbenzene	0.0705	120.2	0.00099	↑
52	n-decane	0.0140	142.3	0.00202	
53	methylpropylbenzene	0.017	134.2	0.00050	
54	dimethylethylbenzene	0.0289	134.2	0.00035	
55	n-undecane	0.0075	156.3	0.00030	
56	1,2,4,5-tetramethylbenzene	0.0056	134.2	0.00022	
57	1,2,3,4-tetramethylbenzene	0.0704	134.2	0.00016	
58	1,2,4-trimethyl-5-ethylbenzene	0.0651	148.2	0.00014	
59	n-dodecane	0.000	170.3	0.00020	
60	nanthalene	0.0076	128.2	0.00006	↓

1.00000 = Sum of Mass Fractions (should be =1)

How Do I Measure a Distribution?
Return to Vapor Conc. Estimation Card
Print Lists

Figure VE-3. The compound list with molecular weight and vapor pressure at 10 °C.

H16

Help: Compound List

'Weathered'
Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 10 °C	
53	methylpropylbenzene	0.017	134.2	0.00050	<div style="border: 1px solid black; width: 20px; height: 20px; margin: 0 auto; display: flex; align-items: center; justify-content: center;"> <div style="margin-bottom: 5px;">↑</div> <div style="margin-top: 5px;">↓</div> </div>
54	dimethylethylbenzene	0.0289	134.2	0.00035	
55	n-undecane	0.0075	156.3	0.00030	
56	1,2,4,5-tetramethylbenzene	0.0056	134.2	0.00022	
57	1,2,3,4-tetramethylbenzene	0.0704	134.2	0.00016	
58	1,2,4-trimethyl-5-ethylbenzene	0.0651	148.2	0.00014	
59	n-dodecane	0.000	170.3	0.00020	
60	naphthalene	0.0076	128.2	0.00006	
61	n-hexylbenzene	0.0147	162.3	0.00005	
62	methylnaphthalene	0.0134	142.2	0.00002	

1.00000 = Sum of Mass Fractions
(should be =1)

How Do I Measure a Distribution?
Return to Vapor Conc. Estimation Card
Print Lists

Figure VE-4. The vapor concentration and critical volume estimation.

Model Predictions

①

To the right is a summary of the data you have input. If you wish to change any of the info, then click on the parameter name, and redo the calculations on the card you will be taken to. Press the blinking 'Return' button to come back

②

The model returns output that allows you to determine residual amounts of compounds falling within 5 boiling point ranges. Type in your own ranges, or choose the default values.

③

--> Set Default BP Ranges <--

Boiling Point Range #1	-50	to	28	C
Boiling Point Range #2	28	to	80	C
Boiling Point Range #3	80	to	111	C
Boiling Point Range #4	111	to	144	C
Boiling Point Range #5	144	to	250	C

④

Generate Predictions

Temperature (°C) 10

Soil Type User Defined

Soil Permeability Range (darcy) 270 to 305

Well Radius (in) 2

Radius of Influence (ft) 120

Contaminant Type Weathered Gasoline

Permeable Zone Thickness (ft) 20

tell me more about BP ranges...

16

Print Card

①

--> Import Data <--

FIRST PRESS THE IMPORT DATA BUTTON!

These are the results for the contaminant type that you have

Saturated Vapor Concentration at time=0 0.1477E+03 [mg/L]

Min Volume to Remove >90% of Initial Residual 221.25 [L-air/g-residual]

Temperature (°C): 10

Contaminant Type: Weathered Gasoline

Qt/M(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.000	100.000	.690	11.650	24.010	22.140	41.510
.34	72.157	95.000	.066	9.223	24.040	23.030	43.641
.81	55.766	90.025	.000	6.613	23.541	23.877	45.969
1.41	45.406	85.037	.000	4.333	22.456	24.667	48.544
2.16	36.693	80.037	.000	2.429	20.788	25.378	51.405
3.08	29.361	75.037	.000	1.041	18.434	25.934	54.590
4.23	23.647	70.042	.000	.285	15.350	26.226	58.140
5.67	19.176	65.046	.000	.044	11.711	26.134	62.111

Launch Excel

17

Print Card

Figure VE-4. The vapor concentration and critical volume estimation.

① --> Import Data <--

specified. All of this information has also been written to a spreadsheet compatible file, named IDEAL MODEL PREDICTIONS, which may be

Saturated Vapor Concentration at time=0 [mg/L]

Min Volume to Remove >90% of Initial Residual [L-air/g-residual]

Temperature (°C):

Contaminant Type:

QtM(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
7.43	15.123	60.046	.000	.002	7.903	25.519	66.576
9.67	11.321	55.048	.000	.000	4.325	24.105	71.570
12.66	8.072	50.058	.000	.000	1.522	21.428	77.050
16.85	5.915	45.104	.000	.000	.239	17.002	82.759
22.57	4.347	40.128	.000	.000	.000	11.418	88.582
30.36	3.176	35.168	.000	.000	.000	6.017	93.983
41.01	2.254	30.199	.000	.000	.000	1.734	98.266
56.02	1.597	25.284	.000	.000	.000	.000	100.000

Launch Excel Print Card

① --> Import Data <--

expressed as a percentage of the concentration at time=0, which is displayed in the upper right corner.

Saturated Vapor Concentration at time=0 [mg/L]

Min Volume to Remove >90% of Initial Residual [L-air/g-residual]

Temperature (°C):

Contaminant Type:

QtM(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
56.02	1.597	25.284	.000	.000	.000	.000	100.000
77.21	1.084	20.324	.000	.000	.000	.000	100.000
108.42	.683	15.437	.000	.000	.000	.000	100.000
158.00	.535	10.580	.000	.000	.000	.000	100.000
221.25	.416	5.709	.000	.000	.000	.000	100.000
302.69	.151	1.698	.000	.000	.000	.000	100.000
379.02	.092	.334	.000	.000	.000	.000	100.000
403.68	.092	0.000	.000	.000	.000	.000	100.000

Launch Excel Print Card

Figure VE-5. The removal rate estimation.

Removal Rate Estimates

The maximum achievable removal rate occurs whenever the vapors removed by venting are "saturated" or in equilibrium with the contaminant/soil matrix.

The "Removal Rate" is simply the product of the flowrate times the vapor concentration. The values you input on Cards 8 & 10 will be used to generate removal rate estimates.

Maximum Removal Rate = Maximum Vapor Concentration x Estimated Vapor Flowrate

We calculate this "maximum" removal rate to determine if, even under the best conditions (saturated vapors & no composition changes w/time), venting can meet your needs.

Click on the button below to generate these values...

Calculate Estimates

11

Maximum Removal Rate Estimates

select your unit preference below

☐ [lb/d]

☒ [kg/d]

Note:

These are "maximum removal rates", and should only be used as screening estimates to determine if venting is even feasible at a given site. Continue on to the next card to assess if these rates are acceptable...

Temperature (°C)
Soil Type
Soil Permeability Range (darcy)
Well Radius (in)
Radius of Influence (ft)
Contaminant Type
Permeable Zone Thickness (ft)

10	
User Defined	
270	to 305
2	
120	
Weathered Gasoline	
20	

P_w - Well Vacuum (in H₂O)

5
10
20
40
60
120
3

Flowrate Estimates [SCFM] (single well)

226.03	to	255.33
449.26	to	507.49
887.33	to	1002.36
1729.94	to	1954.19
2527.82	to	2855.50
4653.12	to	5256.30
135.95	to	153.57

Max. Removal Rate Estimates [kg/d] (single well)

1332	to	1504
2680	to	3028
5431	to	6135
11166	to	12613
17257	to	19494
38411	to	43390
797	to	900

12

Print Card

Figure VE-6. The determination of "Is soil venting appropriate?".

Is Soil Venting Appropriate?

At this point, you compare the maximum possible removal rate with your desired removal rate.

If the maximum removal rate does not exceed your desired removal rate, then soil venting is not likely to meet your needs, and you should consider another treatment technology, or make your needs more realistic.

In the next cards, we will refine

Enter Estimated Spill Mass ☒ kg ☐ lb

Enter Desired Remediation Time days

--> Press to get Rates <--

Single Vertical Well Results

Desired Removal Rate:	<input type="text" value="255"/>	[kg/d]
Gauge Vacuum (in H ₂ O):	<input type="text" value="3"/>	[in H ₂ O]
Min Flowrate @ 3 in H ₂ O	<input type="text" value="135.95"/>	[SCFM]
Max Flowrate @ 3 in H ₂ O	<input type="text" value="153.57"/>	[SCFM]
Max. Est. Removal Rate:		
(lower estimate) - per well	<input type="text" value="797.280"/>	[kg/d]
(upper estimate) - per well	<input type="text" value="900.564"/>	[kg/d]

13

Help: Boundary Layer Equations - Calculation

1 Soil Type (choose one)

☐ Medium Sand ☐ Clayey Silts

☐ Silty Sand ☐ Fine Sand

☒ Input Your Own Permeability Range

to [darcys]

2 Process Variables:

thickness of screened interval [ft]

radius of influence of venting well [ft]

venting well radius [in]

applied vacuum at well [in H₂O]

radial width of contaminated zone

3 --> Calculate <--

Just enter values into the appropriate fields, then click on the "calculate" button.

The "Relative Efficiency" is the ratio of the predicted removal rate to the removal rate that would be obtained if the extracted vapors were saturated, or in equilibrium with the liquid

Relative Efficiency = to (%)

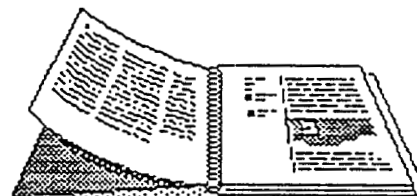
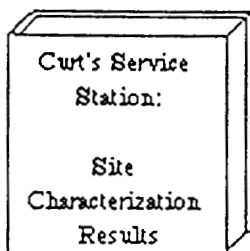
Return H29

Figure VE-7. HyperVentilate software aid system design.

System Design...

For the system design process, you should assemble the following information:

- site plans (showing subsurface utilities, tanks, surface structures, etc.)
- plots of the subsurface (geologic cross-sections, water table maps, and soil boring and ground water sampling results)
- contaminant composition (or boiling point distribution)
- air permeability test data (permeability values & vapor concentrations)
- aquifer characteristics (ground water gradient, aquifer permeability, etc.)



Design Input

(soil stratigraphy & contaminant characteristics)

Please enter the required information for each distinct soil layer, click on the "Update" button, and then proceed to the next card (i.e. click on right arrow at bottom).

(the tab key can be used to move between cells)

Select the total mass units that you prefer

☒ [kg]

☐ [lb]

Clear All Entries

Description of Soil Unit		Depth BGS* [ft]			Description of Contamination	Contaminant Distribution			Calc. Total Mass [kg]
						radius [ft]	interval thickness [ft]	average conc. [mg/kg]	
1	sand	70	to	90	old jet fuel	391	20	342	158064.0
2			to						0.0
3			to						0.0
4			to						0.0
5			to						0.0
6			to						0.0
7			to						0.0
8			to						0.0

* Below Ground Surface

Update



Return



SD2

Figure VE-7. HyperVentilate software aid system design.

Design Input

Please enter the required information for each distinct soil layer, and then proceed to the next card.

Note: - click on any table heading to get more info
- use tab key to move between cells

☐ Medium Sand
☐ Fine Sand
☐ Silty Sand
☐ Clayey Silts

Description of Soil Unit		Permeability* [darcy]			Design Vacuum (in H ₂ O)	Extraction Well Construction			Critical Volume of Air** [L/g]	Efficiency (%)
						well radius [in]	screen thickness [ft]	radius of influence [ft]		
1	sand	270	to	305	3	2	20	120	221.25	25
2			to							
3			to							
4			to							
5			to							
6			to							
7			to							
8			to							

* Enter or choose from list at top right ** minimum volume of vapor required to achieve remediation

Clear All Entries
 Return
SD3

Design Input

Please enter (1) the desired time period for remediation, (2) the design gauge vacuum, and then (3) click the "update" button.

Note: - click on any table heading to get more info
- use tab key to move between cells

(3) Update

(1)
(2)

Description of Soil Unit		Time for Clean-up [days]	Design Vacuum (in H ₂ O)	Flowrate per Vapor Extraction Well [SCFM]		Minimum Number of Wells				
						Based on Area	Based on Critical Volume**			
1	sand	730	3	135.9	to	153.5	10.6	30.4	to	34.3
2				NA	to	NA	NA	NA	to	NA
3				NA	to	NA	NA	NA	to	NA
4				NA	to	NA	NA	NA	to	NA
5				NA	to	NA	NA	NA	to	NA
6				NA	to	NA	NA	NA	to	NA
7				NA	to	NA	NA	NA	to	NA
8				NA	to	NA	NA	NA	to	NA

NA - not enough input data ** minimum volume of vapor required to achieve remediation

Clear All Entries
 Return
SD4

AIR PERMEABILITY

The air permeability of soil is not only the key parameter to determine if SVE a feasible remedial alternative but also an important factor for SVE system design criteria (Johnson et al., 1990b). The air permeability of soil at vadoze zone can be determined from literature values and laboratory or field test. The unit used for soil air permeability is "darcys" or cm^2 and has the units of length squared. The literature and laboratory tests usually provide the permeability of the dry soil matrix, this intrinsic permeability could not represent the actual condition on site. A pneumatic permeability can be estimated from field tests while soil moisture taking up some of the soil pore space. The pneumatic permeability is generally smaller than the intrinsic permeability but will increase along the SVE operation and close to the intrinsic permeability.

Data were obtained during the SVE pilot test for better estimate of the air permeability to be used in the SVE system design. Air pressure changes were monitored at the wells WT-17, WT-13, OW-1, and OW-2 located at 31 ft, 80 ft, 117 ft, and 150 ft from the extraction well. The flow rate applied at the extraction well were 100 scfm, 150 scfm, 180 scfm. The test for flow rate at 180 was operated on two separate days.

The computer modeling program "HyperVentilate" - a decision-support software -developed by EPA and Shell Oil Company is used to assist the estimation for the pneumatic permeability, and evaluate the system design parameters. Due to the invisible variables underground such as the actual amount of liquid form contaminants, moisture contents; the modeling results may be somewhat different from the actual air permeability at the time when the SVE system is operating. However, the results from this software output are judged to be in the reasonable range for use.

Air permeability tests use airflow and transient air pressure measurements taken during SVE pilot test to estimate the permeability at the vadoze zone of the soil matrix. The time period of transient air pressure change during SVE operation was obtained by plotting the pressure changes in inches of water versus log time in hours. The corresponding time period for the transient air pressure was taken from the estimated linear range of pressure changes manually selected. The graphical analysis of the optimum time period for data selection are presented in figure AP-1 to AP-3 and table AP-1. After the time interval was selected, the pressure changes and its corresponding time, air flow, radial distances of monitoring points (wells), screened interval thickness were keyed in to the software for estimation. The Air Permeability Test - Data Analysis were presented as figure AP-4 to AP-6.

A sensitivity test was run on both higher and lower run time span for selected data to get the best fit of this estimation. The presented results are only the best fit estimations in order to save the volume of this report.

The data for flow rate at 100 SCFM were not used for air permeability estimation because this run was conducted during the first day's operation. The flow rate was not stable until several adjustment was done. Therefore, the transient air pressure measurements were not appropriate for this estimation.

RESULT OF THE AIR PERMEABILITY ESTIMATION

Data for one run of 150 SCFM and two run of 180 SCFM were analyzed by the HyperVentilate. The results showing in table AP-1 indicate that the result at OW-2 (150 ft) and the second run of 180 SCFM did not give good fitting in the program because the correlation coefficients were less than 0.9. The estimated air permeability for 150 SCFM and first run of 180 SCFM associated with WT-13 (31 ft), WT-17 (80 ft), and OW-1 (117 ft) were used to calculate the average estimated air permeability. The results of estimated air permeability is presented in table AP-2. The average estimated air permeability is 305 darcy with a average correlation coefficient of 0.946.

Table AP-1. Time period used for data selections

Flow Rate SCFM	Radial distance from the extraction well to monitoring wells			
	31'	80'	117'	150'
	Time (min)			
150	4-13.5	4-15	4-13.5	17-24.5
180-1	1.5-10	2-10	3-11.5	3-12
180-2	2-14	2.5-20.5	1.5-12.5	1.5-30.5

Table AP-2. Estimated air permeabilitie (Darcy)

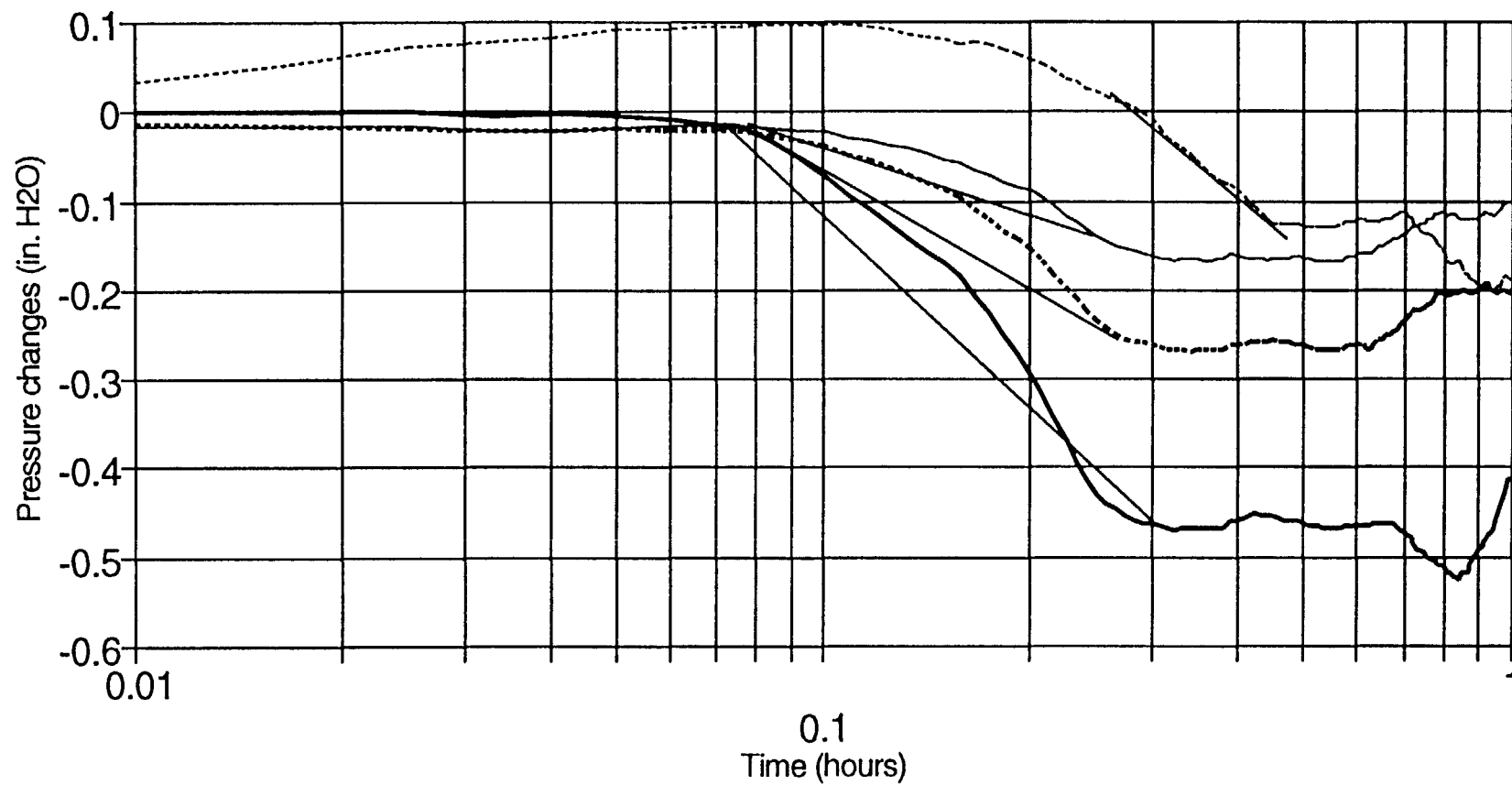
Flow Rate SCFM	Radial distance from the extraction well to monitoring wells				
		31'	80'	117'	150'
150	Darcy	142.637	235.855	336.206	404.629
	Cor. Coef.	0.948	0.959	0.913	0.391
180-1	Darcy	174.631	354.771	583.959	405.297
	Cor. Coef.	0.958	0.966	0.935	0.342
180-2	Darcy	346.906	708.369	874.322	1221.52
	Cor. Coef.	0.818	0.865	0.835	0.853

AVG AIR PERMEABILITY= 305 Darcy

AVG CORR. COEFF. = 0.946

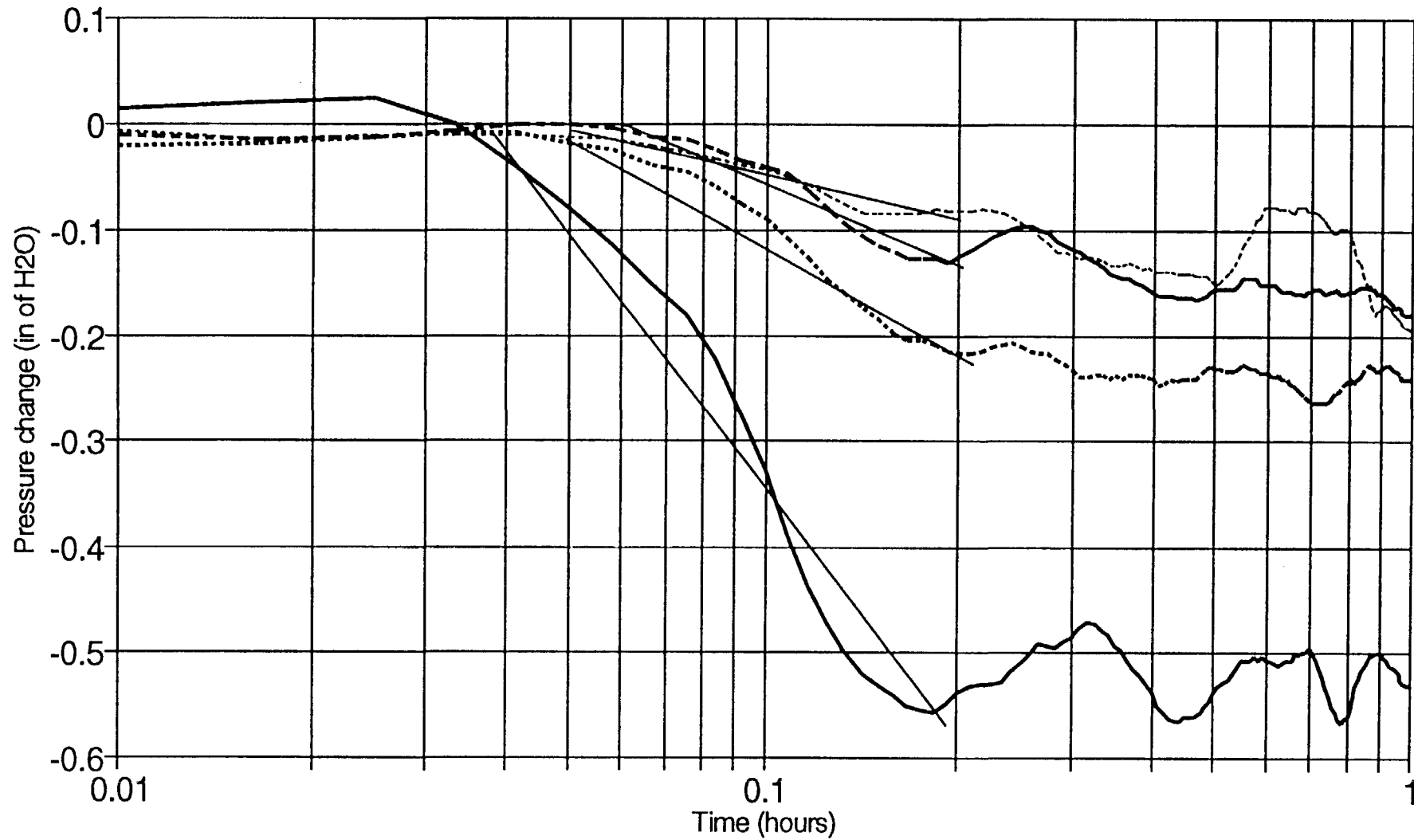
NOTE: data with Cor. Coeff. < 0.9 were not used for average value calculation

Figure AP1 Air Pressure Changes 150 CFM
Soil Vapor Extraction Pilot Study



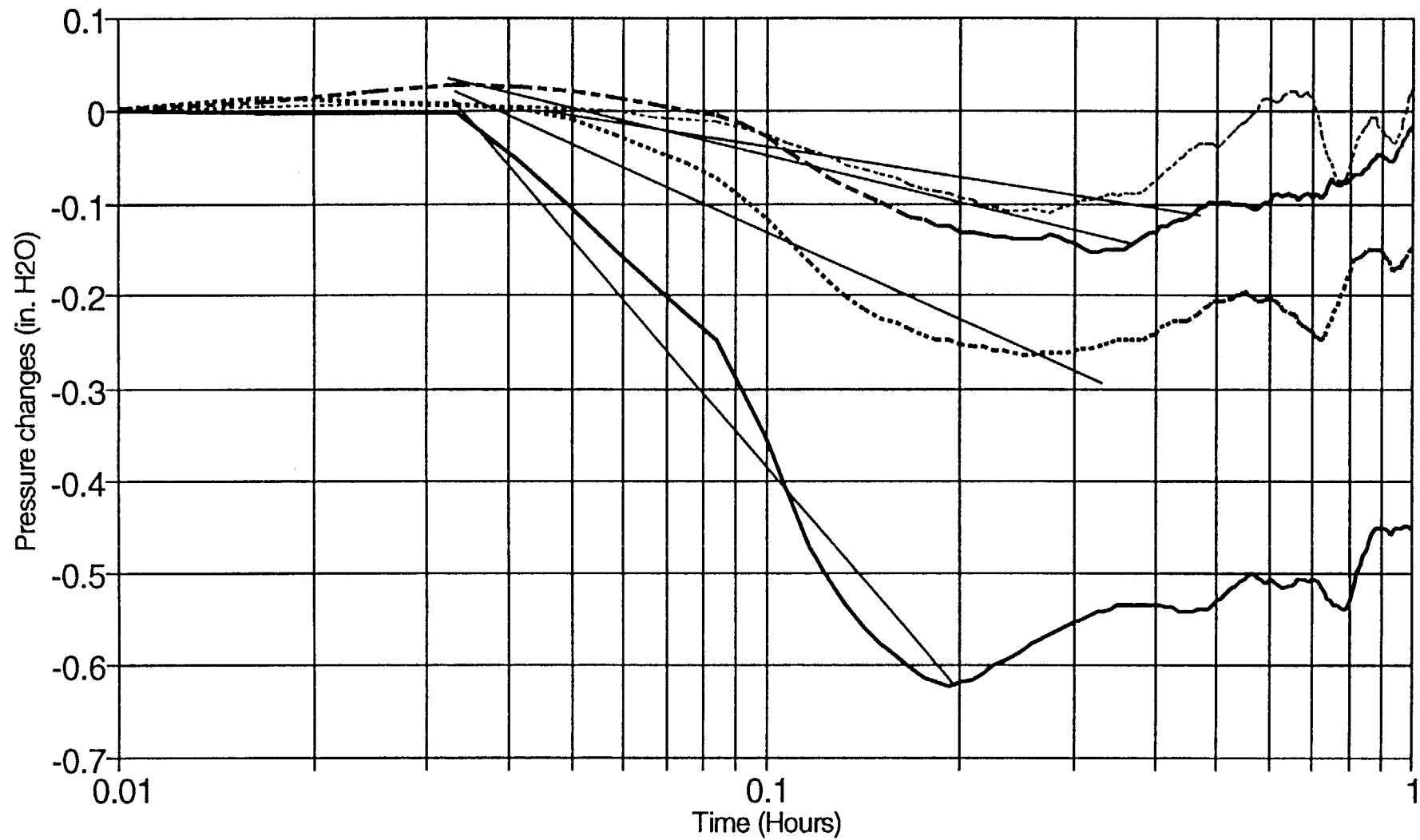
— WT-17(31') WT-13(82') — OW-1(117') OW-2(150')

Figure AP2 Air Pressure Changes 180 CFM
Soil Vapor Extraction Pilot Study



— WT-17 WT-13 - - - - OW-1 OW-2

Figure AP3 Air Pressure Changes 180 CFM
Soil Vapor Extraction Pilot Study



— WT-17 WT-13 ---- OW-1 - . - . OW-2

Figure AP-4. Presentation of Air Permeability Test - Data Analysis for 150 CFM

Air Permeability Test - Data Analysis (cont.)

Enter radial distances of monitoring points → r= (ft)

Enter measured times and gauge vacuums →

Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

r= (ft)

(min) (in H₂O)

4	.0338
4.5	.0676
5	.2027
5.5	.2533
6	.3209
6.5	.3378
7	.3547
7.5	.3547
8	.4053
8.5	.4222

clear

r= (ft)

(min) (in H₂O)

4	.0168
4.5	.02534
5	.04222
5.5	.03378
6	.05911
6.5	.08445
7	.10978
7.5	.10134
8	.10134
8.5	.14356

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return
Explanation & Statistics
AP8

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Air Permeability Test - Data Analysis (cont.)

Enter radial distances of monitoring points → r= (ft)

Enter measured times and gauge vacuums →

Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

r= (ft)

(min) (in H₂O)

9	.4138
9.5	.4222
10	.4391
10.5	.4476
11	.46445
11.5	.4391
12	.46445
12.5	.48134
13	.48134
13.5	.56579

clear

r= (ft)

(min) (in H₂O)

9	.16889
9.5	.13511
10	.16889
10.5	.12667
11	.16889
11.5	.13511
12	.13511
12.5	.16889
13	.16045
13.5	.25334

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-4. Presentation of Air Permeability Test - Data Analysis for 150 CFM

Air Permeability Test - Data Analysis (cont.)

1 Enter radial distances of monitoring points → r= (ft)

2 Enter measured times and gauge vacuums →

3 Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

---> Calculate <---

r= (ft)

(min) (in H2O)

9	.4138
9.5	.4222
10	.4391
10.5	.4476
11	.46445
11.5	.4391
12	.46445
12.5	.48134
13	.48134
13.5	.56579

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min) (in H2O)

9	.16889
9.5	.13511
10	.16889
10.5	.12667
11	.16889
11.5	.13511
12	.13511
12.5	.16889
13	.16045
13.5	.25334

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

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Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)
darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points (ln(t), P') are fit to a line. The "correlation coefficient", r, is a measure of how well the data conform to the theoretical curve. As r→1, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r, consult any introductory Statistics book.

Correlation Coef.
(r)

data set #1

data set #2

data set #3

Return
AP9

Figure AP-4. Presentation of Air Permeability Test - Data Analysis for 150 CFM

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

(min) (in H₂O)

4	.0338
4.5	.0676
5	.2027
5.5	.2533
6	.3209
6.5	.3378
7	.3547
7.5	.3547
8	.4053
8.5	.4222

clear

(min) (in H₂O)

4	.0338
4.5	.0338
5	.0591
5.5	.1014
6	.1183
6.5	.1689
7	.1605
7.5	.1858
8	.2027
8.5	.2196

clear

(min) (in H₂O)

17	0.0000
17.5	.1098
18	.1098
18.5	.152
19	.152
19.5	.1267
20	.1013
20.5	.152
21	.1267
21.5	.152

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return

Explanation & Statistics

AP8

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Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

(min) (in H₂O)

9	.4138
9.5	.4222
10	.4391
10.5	.4476
11	.46445
11.5	.4391
12	.46445
12.5	.48134
13	.48134
13.5	.56579

clear

(min) (in H₂O)

9	.2534
9.5	.228
10	.2534
10.5	.2449
11	.2872
11.5	.2196
12	.2703
12.5	.2956
13	.2618
13.5	.3378

clear

(min) (in H₂O)

20	.1013
20.5	.152
21	.1267
21.5	.152
22	.1098
22.5	.1351
23	.1098
23.5	.1098
24	.1267
24.5	.1436

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return

Explanation & Statistics

AP8

Figure AP-4. Presentation of Air Permeability Test - Data Analysis for 150 CFM

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Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)

darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points ($\ln(t)$, P') are fit to a line. The "correlation coefficient", r , is a measure of how well the data conform to the theoretical curve. As $r \rightarrow 1$, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r , consult any introductory Statistics book.

Correlation Coef.

(r)

data set #1 0.947936

data set #2 0.958655

data set #3 0.39007



Return

AP9

Figure AP-5. Presentation of Air Permeability Test - Data Analysis for 180 CFM (1st run)

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

-->Calculate<--

r= (ft)

(min) (in H2O)

1.5	0.000
2	.008
2.5	.253
3	.363
3.5	.414
4	.456
4.5	.481
5	.498
5.5	.523
6	.566

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min) (in H2O)

3	0.000
3.5	.025
4	.042
4.5	.042
5	.059
5.5	.110
6	.101
6.5	.127
7	.101
7.5	.127

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

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Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

-->Calculate<--

r= (ft)

(min) (in H2O)

6	.566
6.5	.583
7	.591
7.5	.616
8	.633
8.5	.659
9	.625
9.5	.616
10	.633

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min) (in H2O)

7.5	.127
8	.101
8.5	.101
9	.127
9.5	.118
10	.127
10.5	.152
11	.143
11.5	.152

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-5. Presentation of Air Permeability Test - Data Analysis for 180 CFM (1st run)

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

--> Calculate <--

r= (ft)

(min) (in H2O)

1.5	0.000
2	.008
2.5	.253
3	.363
3.5	.414
4	.456
4.5	.481
5	.498
5.5	.523
6	.566

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min) (in H2O)

3	0.000
3.5	.025
4	.042
4.5	.034
5	.042
5.5	.059
6	.059
6.5	.085
7	.076
7.5	.085

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

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Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

--> Calculate <--

r= (ft)

(min) (in H2O)

6	.566
6.5	.583
7	.591
7.5	.616
8	.633
8.5	.659
9	.625
9.5	.616
10	.633

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min) (in H2O)

6	.211
6.5	.228
7	.228
7.5	.253
8	.245
8.5	.253
9	.228
9.5	.270
10	.278

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-5. Presentation of Air Permeability Test - Data Analysis for 180 CFM (1st run)

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Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)

darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points ($\ln(t)$, P') are fit to a line. The "correlation coefficient", r , is a measure of how well the data conform to the theoretical curve. As $r \rightarrow 1$, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r , consult any introductory Statistics book.

Correlation Coef.
(r)

data set #1 0.957993

data set #2 0.965672

data set #3 0.93489



Return

AP9

Figure AP-5. Presentation of Air Permeability Test - Data Analysis for 180 CFM (1st run)

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Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)

darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points ($\ln(t)$, P') are fit to a line. The "correlation coefficient", r , is a measure of how well the data conform to the theoretical curve. As $r \rightarrow 1$, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r , consult any introductory Statistics book.

Correlation Coef.
(r)

data set #1 0.957993

data set #2 0.965672

data set #3 0.342455



Return

AP9

Figure AP-6. Presentation of Air Permeability Test - Data Analysis for 180 CFM (2nd run)

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate
 (SCFM)

b) screened interval thickness
 (ft)

-->Calculate<--

r= (ft)

(min)	(in H2O)
2	.1014
2.5	.2449
3	.3125
3.5	.3547
4	.4391
4.5	.4391
5	.4307
5.5	.50669
6	.51513
6.5	.54891

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min)	(in H2O)
1.5	0.000
2	.1436
2.5	.2871
3	.3547
3.5	.3969
4.5	.4813
5	.4729
5.5	.5489
6	.5573
6.5	.5911

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min)	(in H2O)
2.5	.0085
3	.076
3.5	.076
4	.1436
4.5	.1039
5	.1351
5.5	.2027
6	.1605
6.5	.1774
7	.1774

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

HyperVentilate© 1991

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate
 (SCFM)

b) screened interval thickness
 (ft)

-->Calculate<--

r= (ft)

(min)	(in H2O)
7	.58269
7.5	.59113
8	.58269
8.5	.5658
9	.54046
9.5	.54891
10	.52357
10.5	.54891
11	.54891
11.5	.4645

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min)	(in H2O)
7	.6249
7.5	.6333
8	.6249
8.5	.608
9	.5827
9.5	.5911
10	.5658
10.5	.5911
11.5	.5067
12	.5151

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min)	(in H2O)
7.5	.2027
8	.2027
8.5	.2196
9	.2449
9.5	.2449
10	.2027
10.5	.2027
11	.2027
11.5	.228
12	.1943

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-6. Presentation of Air Permeability Test - Data Analysis for 180 CFM (2nd run)

Air Permeability Test - Data Analysis (cont.)

Enter radial distances of monitoring points → $r =$ (ft)

Enter measured times and gauge vacuums →

Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

--> Calculate <--

$r =$ (ft)

(min)	(in H ₂ O)
10	.52357
10.5	.54891
11	.54891
11.5	.4645
12	.4729
12.5	.54891
13	.54046
13.5	.5658
14	.52357

clear

k = darcy (A)
k = darcy (B)

$r =$ (ft)

(min)	(in H ₂ O)
9.5	.5911
10	.5658
10.5	.5911
11.5	.5067
12	.5151
12.5	.5911
13	.5827
13.5	.608
14	.5658

clear

k = darcy (A)
k = darcy (B)

$r =$ (ft)

(min)	(in H ₂ O)
13	.1858
13.5	.1943
14	.2196
14.5	.2196
15	.2365
15.5	.2449
16	.2449
16.5	.2027
17	.2703
17.5	.2449

clear

k = darcy (A)
k = darcy (B)

Return
Explanation & Statistics
AP8

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Air Permeability Test - Data Analysis (cont.)

Enter radial distances of monitoring points → $r =$ (ft)

Enter measured times and gauge vacuums →

Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

--> Calculate <--

$r =$ (ft)

(min)	(in H ₂ O)
10	.52357
10.5	.54891
11	.54891
11.5	.4645
12	.4729
12.5	.54891
13	.54046
13.5	.5658
14	.52357

clear

k = darcy (A)
k = darcy (B)

$r =$ (ft)

(min)	(in H ₂ O)
9.5	.5911
10	.5658
10.5	.5911
11.5	.5067
12	.5151
12.5	.5911
13	.5827
13.5	.608
14	.5658

clear

k = darcy (A)
k = darcy (B)

$r =$ (ft)

(min)	(in H ₂ O)
17	.2703
17.5	.2449
18	.2449
18.5	.2449
19	.2196
19.5	.2027
20	.2449
20.5	.2703

clear

k = darcy (A)
k = darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-6. Presentation of Air Permeability Test - Data Analysis for 180 CFM (2nd run)

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Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)

darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points ($\ln(t)$, P') are fit to a line. The "correlation coefficient", r , is a measure of how well the data conform to the theoretical curve. As $r \rightarrow 1$, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r , consult any introductory Statistics book.

Correlation Coef.

(r)

data set #1 0.818413

data set #2 0.863331

data set #3 0.865102



Return

AP9

Figure AP-6. Presentation of Air Permeability Test - Data Analysis for 180 CFM (2nd run)

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

-->Calculate<--

r= (ft)

(min)	(in H2O)
1.5	.0085
2	.0253
2.5	.0253
3	.0085
3.5	.0253
4	.0676
4.5	.0507
5	.0929
5.5	.1098
6	.0929

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min)	(in H2O)
1.5	0
2	.0085
2.5	.0085
3	.0169
3.5	.0422
4	.0676
4.5	.0845
5	.0591
5.5	.0676
6	.0845

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

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Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

-->Calculate<--

r= (ft)

(min)	(in H2O)
6.5	.0676
7	.1351
7.5	.152
8	.1436
8.5	.152
9	.1436
9.5	.1267
10	.1351
10.5	.1013
11.5	.1098

clear

k= darcy (A)
k= darcy (B)

r= (ft)

(min)	(in H2O)
6.5	.0591
7	.0845
7.5	.1098
8	.1014
8.5	.1098
9	.0845
9.5	.0845
10	.0591
10.5	.0676
11	.0422

clear

k= darcy (A)
k= darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-6. Presentation of Air Permeability Test - Data Analysis for 180 CFM (2nd run)

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

r= (ft)

(min)	(in H2O)
7.5	.152
8	.1436
8.5	.152
9	.1436
9.5	.1267
10	.1351
10.5	.1013
11.5	.1098
12.5	.0929

clear

r= (ft)

(min)	(in H2O)
11.5	.0676
12	.0845
12.5	.1098
13	.0845
13.5	.1267
14	.1183
14.5	.1183
15	.1098
15.5	.1267
16	.1183

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return
Explanation & Statistics
AP8

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Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

r= (ft)

(min)	(in H2O)
7.5	.152
8	.1436
8.5	.152
9	.1436
9.5	.1267
10	.1351
10.5	.1013
11.5	.1098
12.5	.0929

clear

r= (ft)

(min)	(in H2O)
16.5	.1267
17	.152
17.5	.1183
18	.1183
18.5	.152
19	.1014
19.5	.1267
20	.1436
20.5	.1689
21	.1183

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-6. Presentation of Air Permeability Test - Data Analysis for 180 CFM (2nd run)

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

r= (ft)

(min)	(in H2O)
7.5	.152
8	.1436
8.5	.152
9	.1436
9.5	.1267
10	.1351
10.5	.1013
11.5	.1098
12.5	.0929

clear

r= (ft)

(min)	(in H2O)
21	.1183
21.5	.1267
22	.1267
22.5	.1436
23	.152
23.5	.1436
24	.1436
24.5	.1267
25	.1267
25.5	.1689

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return
Explanation & Statistics
AP8

HyperVentilate© 1991

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

r= (ft)

(min)	(in H2O)
7.5	.152
8	.1436
8.5	.152
9	.1436
9.5	.1267
10	.1351
10.5	.1013
11.5	.1098
12.5	.0929

clear

r= (ft)

(min)	(in H2O)
26	.1436
26.5	.1267
27	.1267
27.5	.1436
28	.1689
28.5	.1436
29	.152
29.5	.1689
30	.152
30.5	.152

clear

-->Calculate<--

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return
Explanation & Statistics
AP8

Figure AP-6. Presentation of Air Permeability Test - Data Analysis for 180 CFM (2nd run)

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Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)

darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points $(\ln(t), P')$ are fit to a line. The "correlation coefficient", r , is a measure of how well the data conform to the theoretical curve. As $r \rightarrow 1$, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r , consult any introductory Statistics book.

Correlation Coef.
(r)

data set #1 0.835187

data set #2 0.853117

data set #3 No Data



Return

AP9

SECTION 3

Calibration of Soil Vapor Extraction Pilot Study Results with MODFLOW Modeling

CALIBRATION of MODFLOW MODEL to the SOIL VENTING PILOT STUDY RESULTS

INTRODUCTION

A MODFLOW model was developed to model the soil venting pilot studies. The soil permeability of 293 Darcies was used as a starting point in the calibration effort. This was the average permeability that was originally calculated by the Hyperventilate Program using the 150 and 180 SCFM flow rates and the two closest wells. The ratio of vertical to horizontal permeability was adjusted until the Modflow results matched the pilot study results. The ratio that produced the best results was 0.15, which is very close to published values in the range of 0.2 for the outwash sands at Cape Cod. Using this ratio and the 293 Darcies permeability the calibrated MODFLOW analysis was able to match very closely with the pilot study results.

STEPS FOR CALIBRATION

1) Develop parameters to use in MODFLOW model.

The following references will be used for this step:

•"Applying Groundwater Flow Models in Vapor Extraction System Design" J. W. Massman, ASCE Journal of Environmental Engineering, Vol 115, No. 1 Feb. 1989.

•VENTING© Users Guide, Version 1.2 Appendix C, "Analysis of Insitu Vacuum Well Placement Using MODFLOW"

Viscosity of Air @ 10°

$$\mu = 160 \text{ micropoise or } 1.6 \times 10^{-4} \text{ g/cm/sec}$$

Gas Density

$$\rho_a = 1.2 \text{ g/L} = 0.0012 \text{ g/cm}^3 = 0.073 \text{ lbs/ cu. ft.}$$

Molecular Weight of the Air

$$W(m) = 28 \text{ g/mole}$$

Porosity

$$\eta_a = 0.35 \times 0.5 = 0.175 \quad \text{Assuming 50 \% saturation}$$

Gas Conductivity

$$K_i = \frac{\rho_w g K_{ai}}{\rho_a}$$

$$K_i = \frac{1\text{g/cm}^3 * 981\text{cm/sec}^2 * 293\text{Darcies} * 1 \times 10^{-8}\text{cm}^2/\text{Darcies}}{1.6 \times 10^{-4}\text{g/cm-sec}} = 17.96\text{cm/sec}^2$$

$$K_i = 50,910\text{ft/day}$$

Specific Storage

$$S_s = \frac{W(m) \rho_w g \eta_a}{\rho_a R T}$$

$$S_s = \frac{28\text{g/mole} * 1\text{g/cm}^3 * 981\text{cm/sec}^2 * .175}{2.5 \times 10^{10} \frac{\text{cm}^2\text{-g}}{\text{sec}^2\text{-mole}} * 0.0012\text{g/cm}^3} = 0.00016\text{cm}^{-1}$$

$$S_s = 0.0049\text{ft}^{-1} = 0.00041\text{inches}^{-1}$$

2) MODFLOW Input

Flow rates

- 150 scfm = 216,000 scf per day
- 180 scfm = 259,200 scf per day

Model Description

- 30 by 30 grid with 600' by 600' total size
- 3 layers in model
 - 10 foot top layer constant head (h=0)
 - 60 feet middle layer
 - 20 feet bottom well layer
- No flow Boundary around the outside of the model
- Results will be in feet of water because of the units of K and S_s used.

3) Calibration Runs.

The Values of K will be varied until the Model results approximately the results obtained in the field. Table 1. records the data.

TABLE 1. 150 SCFM Pilot Study results vs Modflow Results					
DISTANCE	Pilot Study Results In of H ₂ O	K _x =K _y =K _z = 50,900 ft/day In of H ₂ O	K _x =K _y =K _z = 35,000 ft/day In of H ₂ O	K _x =K _y = 50900 ft/day K _z =.1K _x In of H ₂ O	K _x =K _y = 50900 ft/day K _z =.15K _x In of H ₂ O
0	2.25	0.863	1.25	1.37	1.28
20	0.49	0.311	0.47	0.75	0.66
30	0.45	0.21	0.32	0.6	0.52
40	0.41	0.143	0.21	0.49	0.41
60	0.33	0.073	0.108	0.35	0.283
80	0.25	0.045	0.061	0.27	0.208
100	0.21	0.024	0.037	0.21	0.156
120	0.17	0.015	0.023	0.17	0.121

The calibration run with the K_x=K_y=50,900 and K_z=0.15K_x provide the closest results to the actual air pressure data collected during the pilot study. See figure 1. for a comparison of the various calibration runs.

The calibrated Modflow model was then run with a 180 SCFM flow rate and the results were compared with the pilot study results. Table 2 records the data.

Table 2. 180 SCFM Pilot Study results vs. Modflow Results		
DISTANCE Feet	Pilot Study Results In of H ₂ O	K _x =K _y = 50900 ft/day K _z =.15K _x In of H ₂ O
0	3.22	1.54
20	0.6	0.8
30	0.53	0.61
40	0.472	0.498
60	0.356	0.342
80	0.24	0.249
100	0.2	0.189
120	0.16	0.145

CONCLUSIONS:

The MODFLOW model that use the values of $K_x=K_y=50,900$ ft/day and $K_z=0.15$ kx closely follows the results of the pilot study for both the 150 SCFM and the 180 SCFM tests. These values will be used in the design of the entire system.

Attachments:

The attachments to this section include:

- copies of the surfer plots for the 180 SCFM Modflow model
- copies of the references.

Fig. 1 Model vs. 150 Pilot Study

Soil Vapor Extraction

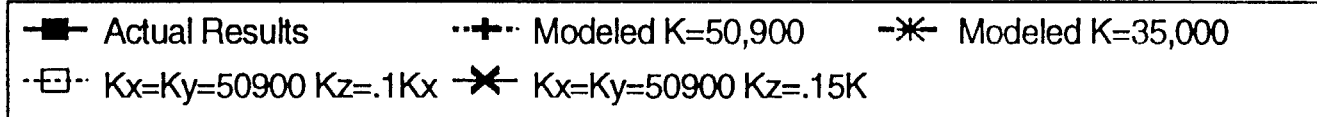
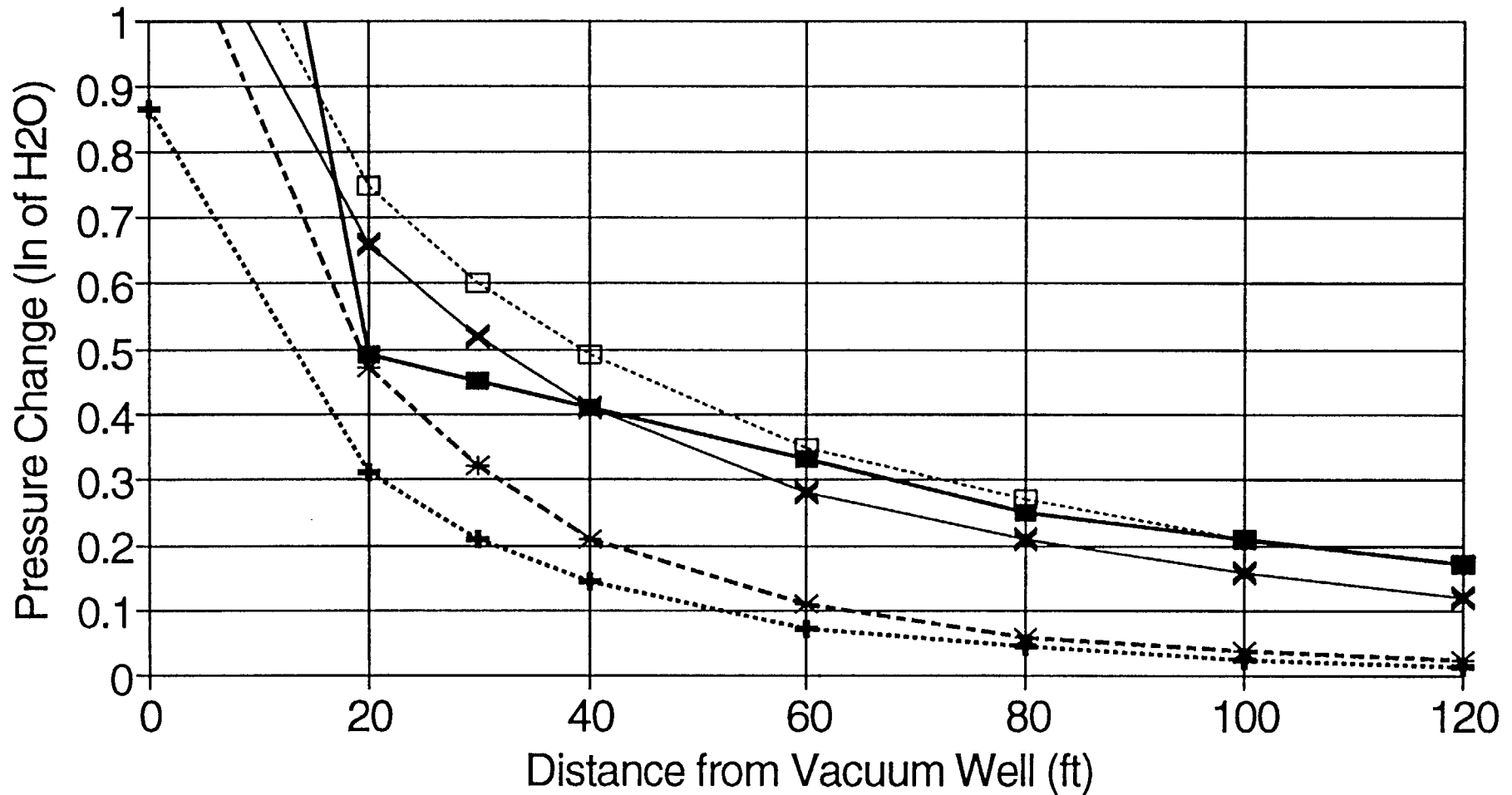
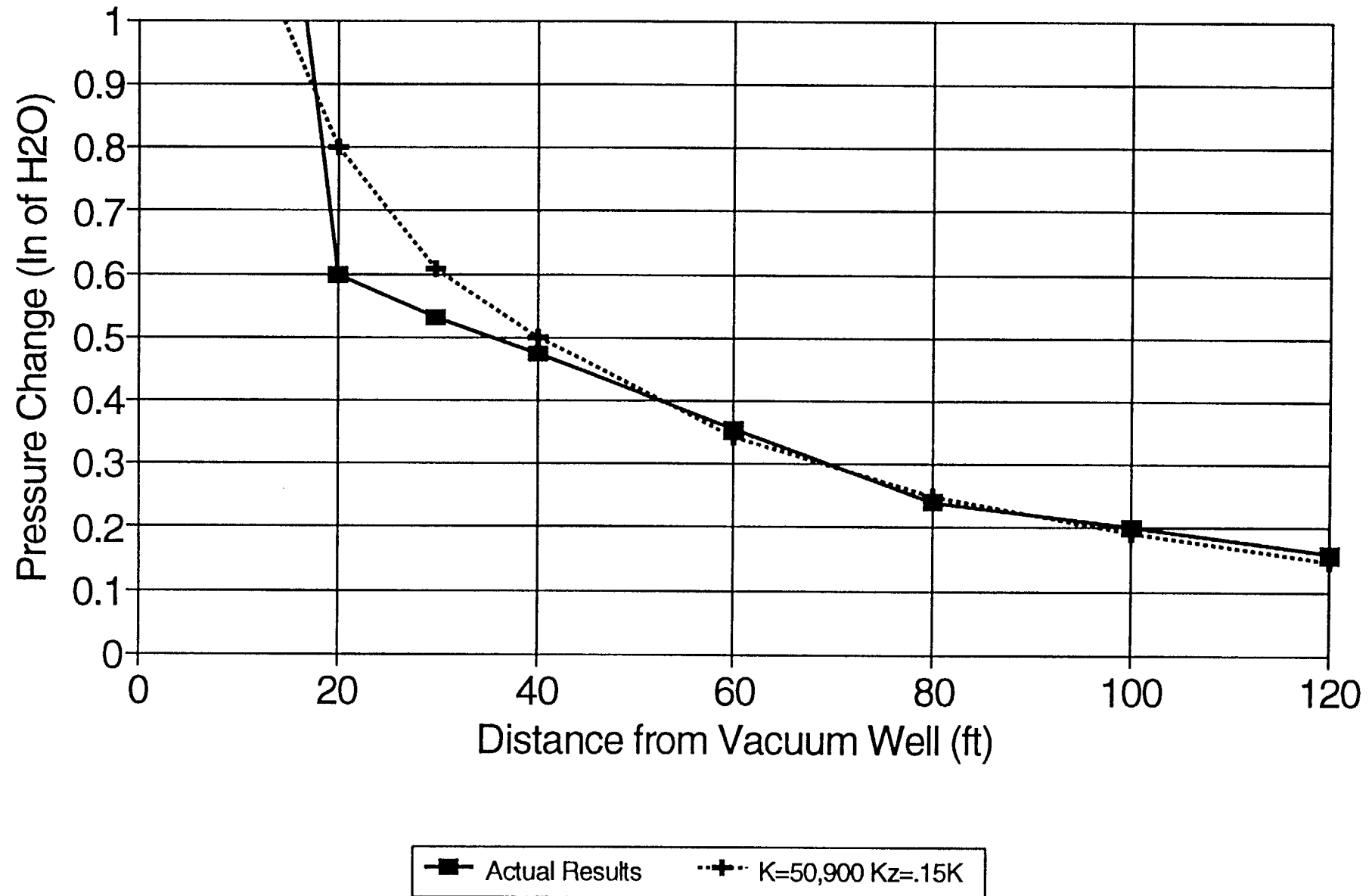
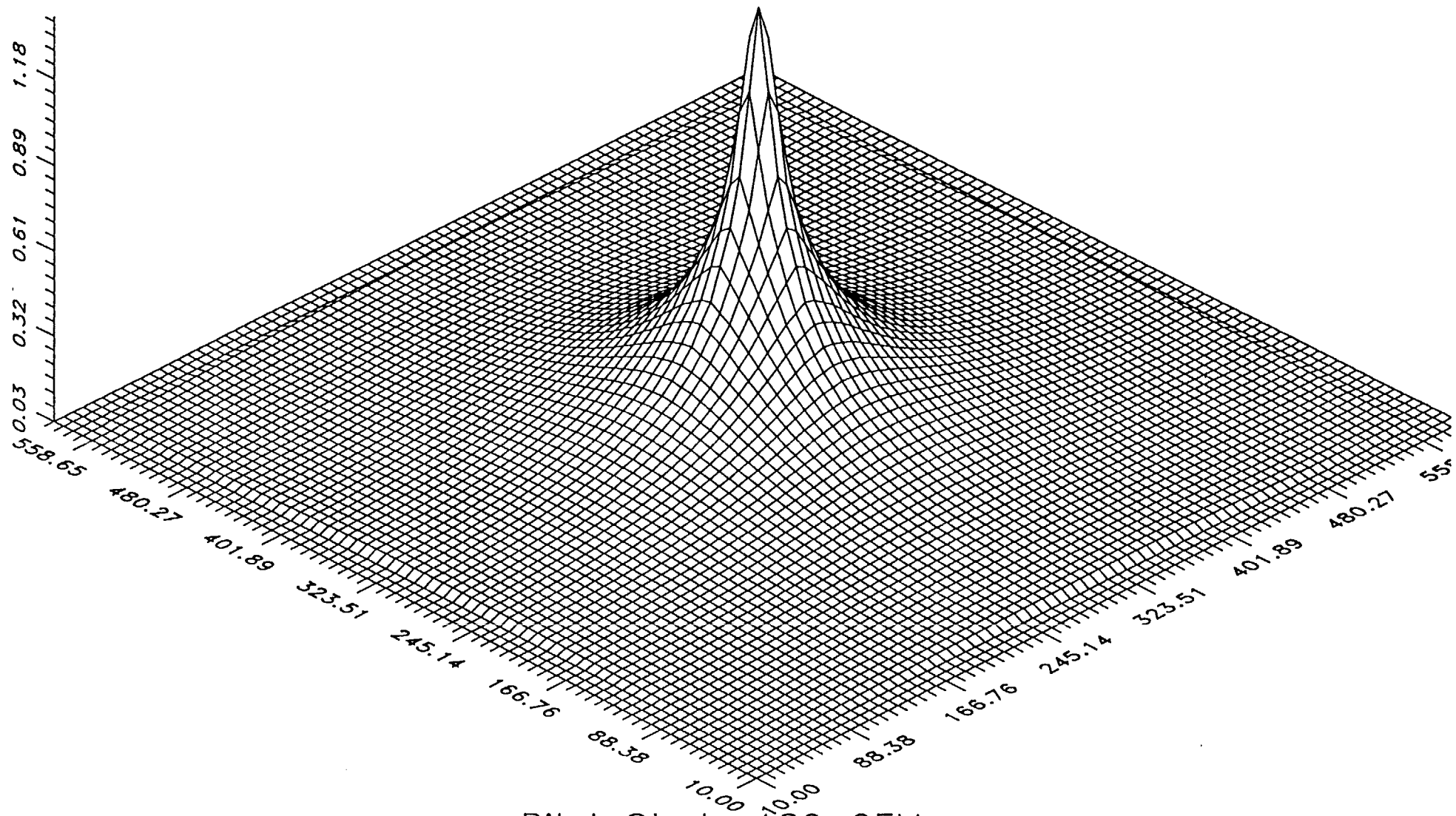
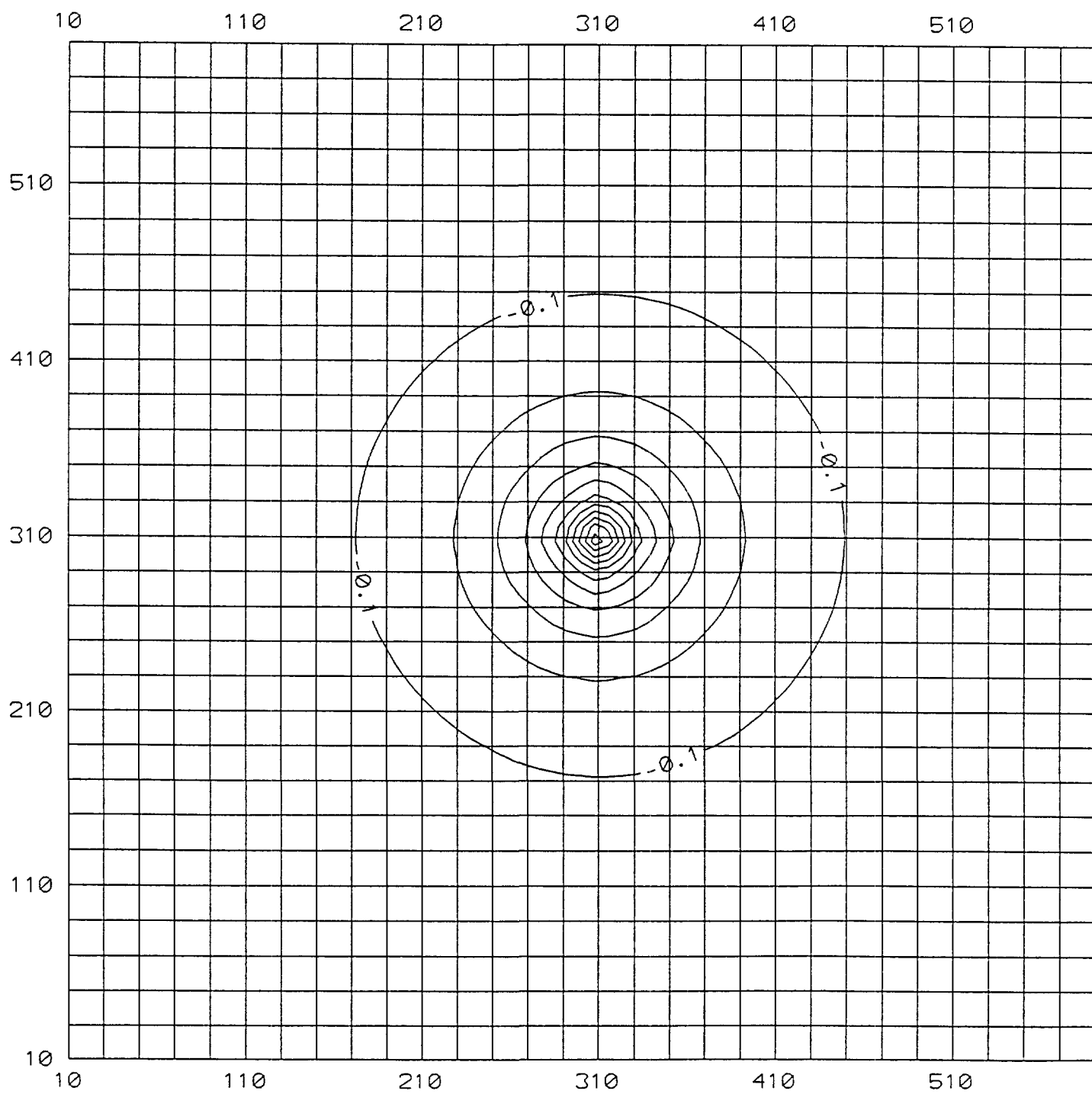


Fig. 2 Model vs 180 CFM Pilot Study Soil Vapor Extraction





Pilot Study 180 CFM



- ϕ = transformation function;
- μ_r = Marquardt parameter;
- ρ_p = apparent adsorbent density (M/L^3);
- σ^2 = standard deviation;
- ∂ = partial derivative;
- ∂^2 = second partial derivative;
- $()^T$ = transpose of a matrix;
- $()^{-1}$ = inverse of a matrix;
- \int = integration;
- Σ = summation; and
- 0 = zero vector.

Subscripts:

- r = derivative with respect to r ;
- rr = second order derivative with respect to r ;
- t = derivative with respect to t .

APPLYING GROUNDWATER FLOW MODELS IN VAPOR EXTRACTION SYSTEM DESIGN

By J. W. Massmann,¹ Associate Member, ASCE

ABSTRACT: Vapor extraction systems have recently been used in a variety of environmental engineering applications, including controlling methane migration and remediating problems associated with spills of volatile and semi-volatile organic compounds. The differential equations that govern pressure flow of gas and vapor in soil are nonlinear in that gas density depends upon gas pressure. However, if the maximum pressure difference between any two points in the flow field is less than approximately 0.5 atmospheres, the differential equations developed to model groundwater flow provide good approximations to gas transport. Vapor extraction systems generally operate under pressure differences on the order of 0.2 atmospheres. Analytical and numerical groundwater flow models can therefore be used to model vapor and gas transport if the proper set of input variables is defined. Analytical groundwater flow models are used to evaluate the results of a field gas extraction test. The results of these evaluations indicate groundwater models can provide an efficient and readily-accessible tool to aid in designing vapor extraction systems.

INTRODUCTION

Several recent environmental concerns have caused an increase in the use of shallow vapor extraction systems. Included in these concerns are the generation and migration of methane gas from landfills and the migration of vapors from spills of petroleum products and other volatile and semi-volatile organic compounds. Methane gas, which is generated within landfills by the bacterial decomposition of organic materials, can migrate through unsaturated soils for distances of hundreds of meters. Although methane is non-toxic, it presents an explosion hazard when mixed with air at concentrations between 5 and 15% by volume. One of the most effective methods to control methane migration is by pumping the methane out of the ground with vapor extraction systems (e.g., Emcon, 1980).

The second principal application of vapor extraction systems is to clean soils contaminated with volatile and semi-volatile organic compounds as a result of leaking underground tanks, pipelines, and other accidental spills. These compounds may be present in the unsaturated zone in both liquid and vapor phases. The liquid portion generally cannot be directly extracted from the unsaturated soils. However, applying a vacuum to the soil will cause the volatile vapors to be removed. As the vapors are extracted, more liquid will vaporize and will be removed from the soil. This application of vapor extraction systems has proven very effective in a number of situations, e.g., Wootan and Voynick (1984), Crow et al. (1985).

A typical vapor extraction system consists of a gas pump or blower connected to a series of wells that have been completed in unsaturated soil. The vacuum from the pump causes gas to flow through the soil to the extraction

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wells. The extraction rates are usually quite low, generally on the order of 15–150 L/s (30–300 cu ft/min) for each extraction well. Pressure drops within the extraction wells are typically less than 7,000 Pascals (30 in. of water or 1 lb/sq in.). Air-injection wells are sometimes used in conjunction with the extraction wells to further control gas flow. Depending upon the application, gas treatment equipment such as carbon adsorption beds may be required before the vapors can be discharged into the atmosphere.

Vapor extraction systems are generally designed using an empirical and site-specific approach. Prototypes or pilot-scale systems are often constructed at each site to determine system parameters such as well depths, well spacings, and extraction rates. One of the reasons that the design process has been primarily empirical is that readily accessible analytical tools have not been available to practicing professionals.

During the same time period that applications of vapor extraction systems have increased, the popularity of prepackaged groundwater flow models has also increased. These models may range from relatively simple analytical models to more complex finite-element or finite-difference numerical models. With a few exceptions, the physical processes on which vapor extraction systems are based are very similar to the physical processes on which groundwater pumping systems are based. It seems natural, then, that groundwater flow models could play a role in the design of vapor extraction systems.

The objective of this paper is to present a methodology for using groundwater flow models as an aid in the design of gas extraction systems. The goal is to obtain approximate results that can be used to infer design parameters. The emphasis of the presentation is on describing methods to predict the number of injection and extraction wells, and the injection and extraction rates, required to obtain a specified pressure drawdown throughout a prescribed zone of influence. This information is required to select blowers and pumps, manifold diameters, and well geometries. Rigorous methods for predicting vapor composition are not included in the development. This information would be required to select vapor treatment equipment if treatment were necessary. Predicting the zones of influence and the sensitivities of these zones to system configurations is of fundamental importance in vapor system design. Predicting time-varying vapor compositions is a more tenuous task and is arguably of secondary importance in many applications.

Although the analytical methods discussed are approximate, they are relatively easy to complete and may result in significant savings in extraction system design. Care has been taken in preparing the paper so that simplifying assumptions are explicitly identified and the limitations that they present are discussed.

DARCY'S LAW AND GAS TRANSPORT IN POROUS MEDIA

The flow of gases and vapors through porous media is treated in a relatively extensive literature, including texts by Satterfield (1970), Geankoplis (1972), and Dullien (1979). The presentation in this section, based in part on the developments by Collins (1961) and Dullien (1979), is intended to illustrate the similarities and differences between the equation of motion for gas flow and the equation of motion for groundwater flow.

The transport of gas or vapor through porous media results from both

pressure and concentration gradients. As stated above, the primary objective is to predict drawdowns in gas pressures caused by extraction systems, rather than to predict gas compositions. Neglecting diffusional flow due to concentration gradients will not have an appreciable impact on gas pressure predictions.

The flow of gases due to pressure gradients differs from the flow of liquids in that the velocity at the pore walls cannot generally be assumed to be zero for gas transport (Dullien 1979). Darcy's law, which governs the flow of liquids in porous media, is based on viscous flow in which the molecular velocity is zero along pore walls. Nonzero velocities at the pore wall will result in greater flow than predicted by Darcy's law. The additional flow is termed "slip flow" or "drift flow." Dullien (1979) presents an expression for the pressure flow of gases that includes the effects of both viscous flow and slip flow:

$$F = -\left(\frac{r^2 p}{8\mu} + \frac{4rRT}{3W_m V_m}\right) \frac{1}{RT} \nabla P \quad (1)$$

where F = molar flux (mole/L²/T); r = average pore radius (L); P = gas pressure (M/L/T²); μ = gas viscosity (M/L/T); R = gas constant (L²/degree K/T²/mole); T = gas temperature (degree K); W_m = molecular weight (M/mole); and V_m = mean molecular velocity (L/T).

The first term on the right side of Eq. 1 accounts for viscous flow and the second term accounts for slip flow. Slip flow is proportional to the average pore radius, whereas viscous or Darcy flow is proportional to the average pore radius squared. The importance of slip flow increases as the average pore radius decreases and as the pressure decreases. The relative importance of slip flow and viscous flow for gas composition, pressure, and temperature conditions typical of vapor extraction systems is illustrated on Fig. 1. For pore radii greater than approximately 10⁻³ mm (4 × 10⁻³ in.), the effects of slip flow are small relative to viscous flow. Silt and clay materials will have pore radii of this magnitude. Sand and gravel materials will have pore radii on the order of 10⁻¹ mm (4 × 10⁻³ in.) and greater.

The magnitude of viscous flow relative to the slip flow for transport in silt, sand, and gravel materials indicates that the equation of motion for gas flow in these types of materials should be of the same form as the equation of motion for groundwater flow, which is given by Darcy's law:

$$q = \frac{-kp}{\mu} \nabla \phi \quad (2)$$

where q = specific discharge (L/T); k = permeability of the soil (L²); μ = viscosity of the fluid (M/L/T); p = density of the fluid (M/L³); and ϕ = fluid potential (L²/T²). The fluid potential for a compressible fluid is given by

$$\phi = gZ + \int_{r_0}^r \frac{dp}{\rho} \quad (3)$$

where P = pressure of the fluid (M/L/T²); Z = elevation (L); and g = gravitational acceleration (L²/T²).

A number of assumptions are required to get Eq. 1 in a form similar to

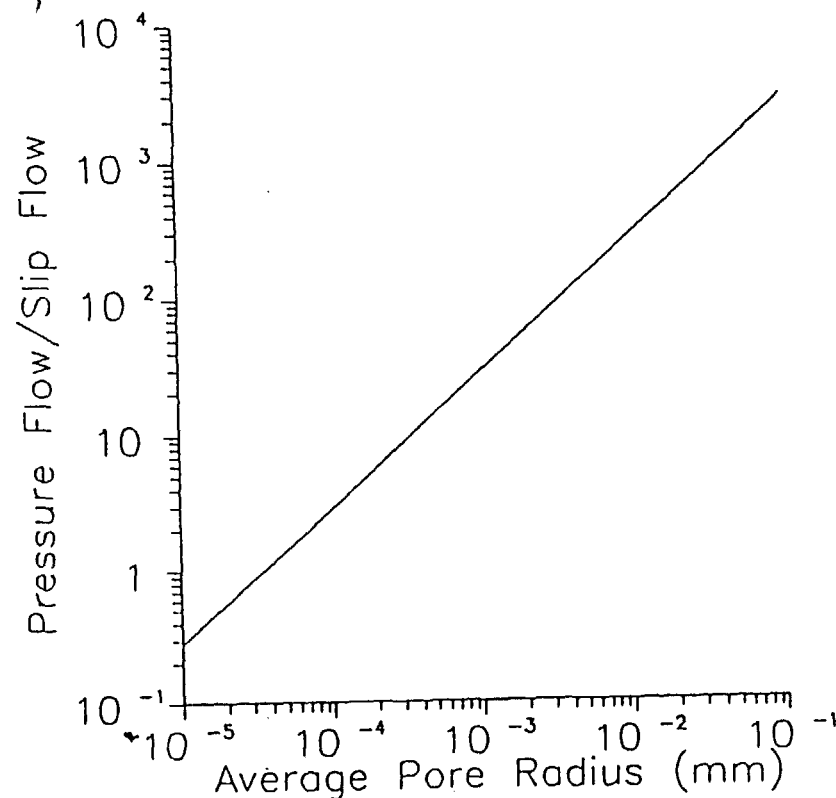


FIG. 1. The Relative Importance of Pressure and Slip Flow for Conditions Typical of Vapor Extraction Systems

Darcy's law. The first assumption is that slip flow can be neglected for flow in sand and gravel materials. Experiments performed by Alzaydi and Moore (1978) show that if pressure gradients typical to those used for vapor extraction systems are imposed across columns containing Ottawa sand, the discharge of air through the samples becomes a linear function of the pressure gradient within a short period of time, as predicted by Darcy's law. These same experiments performed on columns containing kaolinite clay show similar behavior, although more time is required to achieve linear pressure gradients. Their results support the evidence presented on Fig. 1 that Darcy's law provides a good approximation for gas flow in sands and gravels and a fair approximation for flow in silts, clays, and other low-permeability materials.

The second step in relating Darcy's law to gas transport involves expressing volume flux q in terms of molar flux F . The relationship between the two is given by

$$q = \frac{W_m F}{\rho} \quad (4)$$

The driving force for flow in Darcy's law is potential gradient, whereas the driving force in the gas transport equation is pressure gradient. An equation of state relating gas density as a function of gas pressure and temperature is required to convert from potentials to pressures. For the pressures and temperatures used in vapor extraction systems, the gas can be modeled as an ideal gas dependent only upon pressure. The relationship between pressure and density for an ideal gas is given by the Boyle-Mariotte law (Collins 1961):

$$\rho = \frac{W_m P}{RT} \quad (5)$$

Eqs. 3 and 5 can be combined to obtain an expression for fluid potential as a function of pressure:

$$\phi = gZ + \frac{RT}{W_m} \int_{P_0}^P \frac{dP}{P} \quad (6a)$$

$$\phi = gZ + \frac{RT}{W_m} \ln \left(\frac{P}{P_0} \right) \quad (6b)$$

The gradient in potential is given by

$$\nabla \phi = g \nabla Z + \frac{RT}{PW_m} \nabla P \quad (7)$$

The second term on the right side of Eq. 7 is generally much greater than the first term for vapor extraction system applications. The potential gradient can therefore be approximated by

$$\nabla \phi \approx \frac{RT \nabla P}{PW_m} = \frac{\nabla P}{\rho} \quad (8)$$

For many groundwater applications, fluid potential is converted to hydraulic head using the relationship

$$\nabla h = \frac{\nabla \phi}{g} = \frac{\nabla P}{\rho g} \quad (9)$$

Combining Eqs. 2 and 8 gives Darcy's law in terms of pressure gradient:

$$q = \frac{-k \rho \nabla P}{\mu \rho} = \frac{-k}{\mu} \nabla P \quad (10)$$

Finally, combining Eqs. 1, 4, and 10 and neglecting slip flow gives Darcy's law in terms of the gas transport coefficient:

$$q = \frac{-k}{\mu} \nabla P = \frac{W_m F}{\rho} = \frac{-r^2 W_m P}{\rho 8 RT \mu} \nabla P = \frac{-r^2}{8 \mu} \nabla P \quad (11)$$

Eq. 11 shows that the relationship between the Darcy coefficient of permeability and the Dullien coefficient for viscous gas transport is given by

$$k = \frac{r^2}{8} \quad (12)$$

GAS TRANSPORT EQUATIONS AND SIMPLIFYING ASSUMPTIONS

Three general equations are required to model pressure drawdowns caused by vapor extraction systems. These are: (1) A continuity equation; (2) an equation of motion; and (3) an equation of state. The continuity equation is given by

$$\frac{\partial(np)}{\partial t} = -\nabla(pq) \quad (13)$$

where n = porosity of the soil (dimensionless).

As discussed in the previous section, the equation of motion for gas transport can be approximated using the form of Darcy's law given by Eq. 11. The equation of state relating gas density to pressure and temperature is given by Eq. 5, which is based on ideal gas behavior. Eqs. 5, 11, and 13 can be combined to obtain a general transport equation for the transient flow of gas in soils. This equation is of the form

$$\frac{\partial(np)}{\partial t} = \nabla \left(\frac{pk}{\mu} \nabla p \right) \quad (14)$$

A number of simplifying assumptions can be made to get Eq. 14 to look like the groundwater flow equation that is solved by most models. The first assumption that can be made is an outgrowth of the assumption of ideal gas behavior. In most groundwater flow models, the left-hand side of Eq. 14 is given by Freeze and Cherry (1979):

$$\frac{\partial(np)}{\partial t} = \frac{S_s}{g} \frac{\partial p}{\partial t} \quad (15)$$

where S_s = specific storage (L^{-1}).

The term on the left side of Eq. 15 can be expanded using the chain rule to give

$$\frac{\partial(np)}{\partial t} = \frac{n \partial p}{\partial t} + \frac{p \partial n}{\partial t} \quad (16)$$

The second term on the right is negligible compared to the first and can be dropped. Combining Eq. (16) with Eq. 5 gives

$$\frac{\partial(np)}{\partial t} = \frac{n \partial p}{\partial t} = \frac{n W_m}{RT} \frac{\partial p}{\partial t} \quad (17)$$

A comparison of Eqs. 15 and 17 shows that the specific storage term for transport of an ideal gas is given by

$$S_s = \frac{g n W_m}{RT} \quad (18)$$

Eqs. 14, 15, and 18 can be combined to give that equation for transient flow of an ideal gas in a porous media:

$$S_s \frac{\partial p}{\partial t} = \nabla \left(\frac{p g k}{\mu} \nabla p \right) \quad (19)$$

TABLE 1. Summary of Assumptions and Limitations

Assumption (1)	Limitations (2)
The equation of motion for gas transport can be approximated using equation similar to Darcy's law	In fine-grained materials, Darcy's law underestimates discharge by neglecting slip flow; however, assumption is likely valid approximation for flow in sands and gravels
Effects of diffusional flow are negligible	Valid assumption for predicting pressure distributions
Vapor behaves as ideal gas	Valid approximation for temperature and pressure conditions typical of vapor extraction systems
Constant and uniform porosity	Porosity will generally vary with time and with location due to natural variations in geologic materials and due to temporal and spatial variations in moisture content
Molecular weight is uniform	Molecular weight will vary with gas composition; variations will generally be small for typical applications of methane control and organic vapor recovery
Gravitational effects are negligible	Valid assumption for vapor extraction applications
Compressibility of the porous media is negligible	Valid assumption for essentially is small as compared to all systems; compressibility the vapor
Gas transport can be modeled using the equation for incompressible flow	Valid assumption for pressure variations on order of one-half an atmosphere and less

This equation compares to the equation for transient flow of groundwater (Freeze and Cherry 1979):

$$S_s \frac{\partial h}{\partial t} = \nabla(K \nabla h) \quad (20)$$

where K = hydraulic conductivity (L/T).

A summary of the assumptions used to develop a gas transport equation that is in the same form as the groundwater flow equation is presented in Table 1. A brief description of the limitations imposed by these assumptions is also included in Table 1.

The fundamental difference between Eqs. 19 and 20 is that Eq. 19 is nonlinear because of the dependence of gas density on gas pressure. In a strict sense, this nonlinearity does not allow computer models developed to solve the groundwater flow equation to be used to model gas transport. Some type of linearization is required before this can occur. An analytical solution to Eq. 19 for one-dimensional flow in a semi-infinite and homogeneous medium (Kidder 1957) can be used to select this linearization. The equation that Kidder solves is

$$D_1 \frac{\partial P}{\partial t} = \frac{\partial}{\partial x} \left(\frac{P \partial P}{\partial x} \right) \quad (21)$$

TABLE 2. Comparison of Exact and Approximate Solutions to Eq. 21

γ (1)	Exact solution (2)	Eq. 24		Eq. 25	
		Value (3)	Error (4)	Value (5)	Error (6)
(a) $P_i/P_o = 0.90$					
0.00000	0.90000	0.90000	0.00%	0.90000	0.00%
0.10000	0.91201	0.91179	0.02%	0.91125	0.08%
0.20000	0.92360	0.92321	0.04%	0.92227	0.14%
0.40000	0.94475	0.94414	0.06%	0.94284	0.20%
0.80000	0.97571	0.97519	0.05%	0.97421	0.15%
2.00000	0.99957	0.99956	0.00%	0.99953	0.00%
(b) $P_i/P_o = 0.80$					
0.00000	0.80000	0.80000	0.00%	0.80000	0.00%
0.10000	0.82580	0.82492	0.11%	0.82249	0.40%
0.20000	0.85024	0.84863	0.19%	0.84454	0.67%
0.40000	0.89361	0.89119	0.27%	0.88568	0.89%
0.80000	0.95442	0.95245	0.21%	0.94842	0.63%
2.00000	0.99921	0.99916	0.00%	0.99906	0.01%
(c) $P_i/P_o = 0.50$					
0.00000	0.50000	0.50000	0.00%	0.50000	0.00%
0.10000	0.58433	0.57823	1.04%	0.55623	4.81%
0.20000	0.65594	0.64577	1.55%	0.61135	6.80%
0.40000	0.76928	0.75584	1.75%	0.71420	7.16%
0.80000	0.90761	0.89810	1.05%	0.87105	4.03%
2.00000	0.99846	0.99824	0.02%	0.99766	0.08%
(d) $P_i/P_o = 0.20$					
0.00000	0.20000	0.20000	0.00%	0.20000	0.00%
0.10000	0.40031	0.38466	3.91%	0.28997	27.56%
0.20000	0.52597	0.50378	4.22%	0.37816	28.10%
0.40000	0.69742	0.67175	3.68%	0.54271	22.18%
0.80000	0.88395	0.86742	1.87%	0.79368	10.21%
2.00000	0.99811	0.99775	0.04%	0.99626	0.19%

where $D_1 = n\mu/k$.

Eq. 21 is of the same form and has the same terms as Eq. 19. The boundary and initial conditions that Kidder assumes are as follows: $P(x,0) = P_o$ for all x greater than zero; and $P(0,t) = P_i$ for all t greater than zero. The solution to Eq. 21 for several values of P_i/P_o is presented in Table 2. The dimensionless variable Y used to present the solution is given by

$$Y = \sqrt{\frac{D_1}{P_o}} \frac{x}{2\sqrt{t}} \quad (22)$$

Kidder also developed an approximate solution to Eq. 21. This approximation is of the form

$$\frac{P^2 - P_i^2}{P_o^2 - P_i^2} = \text{erf}(Y) \quad (23)$$

where $\text{erf}(Y)$ is the error function of Y .

A comparison of the approximate and exact solutions to Eq. 21 is presented in Table 2 for several values of P_i/P_o . The difference between the two is less than one percent for all values of Y if P_i/P_o is greater than 0.8 and is less than five percent if P_i/P_o is greater than 0.2. Kidder notes that Eq. 23 is the exact solution to the following linear differential equation:

$$\frac{\partial P^2}{\partial t} = \frac{P_o}{D_1} \frac{\partial^2 (P^2)}{\partial x^2} \quad (24)$$

Kidder showed that the values of P/P_o obtained using Eq. 24 differ by less than five percent from the more accurate values obtained using Eq. 21 for all values of P_i/P_o . The largest discrepancy occurs in the extreme case in which P_i/P_o approaches zero. Pressure differences in vapor extraction systems are typically on the order of 10–20% ($P_i/P_o = 0.8$ – 0.9). Given these relatively small pressure differentials, a second approximation to Eq. 21 can be given by

$$\frac{\partial P}{\partial t} = \frac{P_o}{D_1} \frac{\partial^2 P}{\partial x^2} \quad (25)$$

Eq. 25 is a linear differential equation with P as the dependent variable, whereas P^2 is the dependent variable in Eq. 24. The solution to Eq. 25 has the same form as Eq. 23, only written in terms of P instead of P^2 . Solutions to Eq. 25 for several values of P_i/P_o are included in Table 2. The difference between the exact solution for compressible flow (Eq. 21) and the solution to Eq. 25 is less than one percent for all values of Y if P_i/P_o is greater than 0.8. However, the approximation becomes quite poor as P_i/P_o drops below 0.5.

Because the solution to Eq. 25 is very close to the solution of Eq. 21 for P_i/P_o greater than 0.8, it follows that the linear differential equation given by 25 is a close approximation of the nonlinear equation given by 21 for vapor extraction applications. This allows us to rewrite Eq. 19, the equation for gas transport in porous media, as a linear differential equation of the form

$$S_g \frac{\partial P}{\partial t} = \nabla \left(\frac{\rho_o g k}{\mu} \nabla P \right) \quad (26)$$

where ρ_o is the initial gas density.

Eq. 26 is now in the same form as the groundwater flow equation, Eq. 20, with pressure, P , replacing hydraulic head, h , and initial gas conductivity replacing hydraulic conductivity. All the models developed to evaluate groundwater flow can be applied to vapor extraction systems if these replacements are made.

METHODS FOR ESTIMATING INPUT PARAMETERS AND BOUNDARY CONDITIONS

The six input parameters required to model vapor transport using Eq. 26 are the viscosity, initial density, temperature, and molecular weight of the gas, and the porosity and permeability of the porous media. Methods to

TABLE 3. Approximate Viscosities for Typical Gas Components in Vapor Extraction Systems (Weast 1968)

Gas or vapor (1)	Viscosity (Micropoise)	
	30° C (2)	40° C (3)
Air	180	190
Carbon dioxide	148	157
Ethane	90	96
Ethylene	100	106
Methane	108	114
Nitrogen	174	182

Note: 1 micropoise is equal to 1×10^{-8} g/cm/s.

estimate each of these parameters and typical values for vapor extraction systems are discussed below.

Gas Viscosity

The viscosity of a gas mixture is a function of composition and can be estimated using formulas presented by Geankoplis (1972) and Dullien (1979). For most gas mixtures associated with vapor extraction systems, a simple composition-weighted average of viscosities gives a good approximation:

$$\mu_{mix} = \sum_{i=1}^m X_i \mu_i \quad (27)$$

where X_i = mole fraction of component i ; μ_{mix} = viscosity of gas mixture; μ_i = viscosity of component i ; m = number of gas components in the mixture. Viscosities for typical components of concern in methane and organic vapor recovery systems are listed in Table 3.

Gas Density

The initial density of an ideal gas varies inversely with pressure, and varies with molecular composition. Density variations due to changes in composition will depend upon site-specific gas compositions and can be estimated with Eq. 5. Densities for gas compositions typically encountered in vapor extraction system applications will generally vary from approximately 0.7 g/L (0.04 lb/cu ft) for 100% methane to approximately 1.3 g/L (0.08 lb/cu ft) for air with high concentrations of volatile organic vapors.

Molecular Weight

The molecular weight of a gas mixture is equal to the composition-weighted average of the molecular weights of the individual gas components:

$$W_m = \sum_{i=1}^m X_i (W_m)_i \quad (28)$$

where $(W_m)_i$ is the molecular weight of component i .

TABLE 4. Typical Permeability Values for Unconsolidated Geologic Materials (Freeze and Cherry 1979)

Geologic material (1)	Range of permeability (Darcies) (2)
Silt	10^{-1} –1
Silty sand	10^{-2} – 10^1
Clean sand	10^{-1} – 10^3
Gravel	10^1 – 10^4

Porosity

The porosity that should be used in the storage coefficient in Eqs. 18 and 26 is the fraction of the soil volume filled with vapor or gas. Because of the presence of moisture in the soil pores, the air porosity will generally be less than the total porosity. The relationship between air porosity and total porosity is given by

$$n_a = n_t(1 - S) \quad (29)$$

where n_a = air porosity; n_t = total porosity; and S = degree of saturation.

Permeability

Permeability is overwhelmingly the most uncertain and variable of the input parameters included in Eq. 26. Its value can range over more than 13 orders of magnitude, depending upon the type of geologic material and the presence of moisture. Most vapor extraction systems are installed in unconsolidated materials consisting of silts, sands, and gravels. Ranges of permeabilities for dry samples of these materials are summarized in Table 4.

Three general methods for estimating gas permeability are presented in this section. These are: (1) Estimating permeability as a function of saturated hydraulic conductivity; (2) estimating permeability as a function of grain size parameters; and (3) estimating permeability from gas extraction tests.

The relationship between saturated hydraulic conductivity and permeability is given by

$$K = \frac{\rho g k}{\mu} \quad (30)$$

Permeability is a function only of properties of the porous media, while hydraulic conductivity is a function of both porous media properties and fluid properties. For vapor extraction systems that will be operated in dry soils whose saturated hydraulic conductivities are known, Eq. 30 can be solved to obtain permeability by incorporating the viscosity and density of water. For hydraulic conductivities in centimeters per second and gas permeabilities in darcies (1 darcy = approximately 1×10^{-8} cm²), the conversion is given by:

$$k = 1,040 K \quad (31)$$

Gas permeability can also be estimated from grain size analyses performed on soil samples. Eq. 12 presents permeability as a function of pore radius:

$$k = 0.125r^2 \quad (32)$$

Here permeability k and pore radius r are in units of L^2 . For k in darc and r in millimeters, Eq. 32 can be rewritten as

$$k = 125,000r^2 \quad (33)$$

Relationships have been developed to estimate the average pore radius of sands and gravels from the results of grain size analyses. These estimates, which should be viewed as order-of-magnitude approximations, are generally of the form

$$r = cD_{15} \quad (34)$$

where c = empirical constant; and D_{15} = grain size for which 15% by weight of particles are smaller. Sherard et al. (1984) have found that a c value of 0.1 gives reasonable approximations for sand and gravel soils.

Combining Eqs. 33 and 34 gives an expression for gas permeability as a function of the grain size parameter:

$$k = 1,250D_{15}^2 \quad (35)$$

where the permeability, k , is in darcies and the grain size parameter, D_{15} , is in millimeters. It should be emphasized that the permeability value predicted by Eq. 35 is a gross approximation that should be viewed as an order-of-magnitude estimate, at best.

The third general method for estimating gas permeability is from data collected during gas extraction tests. Curve-fitting techniques similar to the Theis, Jacob, and Hantush methods that are used to evaluate groundwater pumping tests can also be used to evaluate these extraction tests. The general procedure for performing extraction tests is to attach a vacuum pump to an extraction well completed in unsaturated soils and to measure pressure draw-downs in adjacent gas probes as a function of time. A plot of pressure draw-down versus time can be used to estimate "gas conductivity" in an approach directly analogous to groundwater pumping tests. Gas permeability can then be estimated from the gas conductivity by incorporating the viscosity and density of gas into Eq. 30. This procedure is presented in more detail in the section describing the case history.

The estimated values for the viscosity, initial density, temperature, and molecular weight of the gas, and the porosity and permeability of the porous media, can be directly incorporated into groundwater flow models to evaluate conceptual designs for vapor extraction systems. A summary of the method is as follows:

1. Estimate gas viscosity using Eq. 27. If no information is available regarding gas composition, assume a viscosity of air equal to 1.8×10^{-4} g/cm/s (0.018 centipoise).
2. Estimate initial gas density based on vapor composition. If no information is available regarding composition, assume a density of air equal to 1.3×10^{-3} g/cm³ (1.3 g/L).
3. Estimate permeability using either Eqs. 30, 31, or 35. Convert into units of cm² by using the conversion of 1 darcy equals 1×10^{-8} cm².
4. Calculate a "gas conductivity" using Eq. 30 and the viscosity, initial density, and permeability from items 1-3. Use a gravitational constant equal to 980 cm/s². The resulting gas conductivity will be in units of cm/s.

5. Estimate the molecular weight of the gas mixture using Eq. 28. If no information is available regarding gas composition, assume a molecular weight of air equal to 28 g/mole.

6. Estimate a storage coefficient using Eq. 18. Use the molecular weight from item 5, the gravitational constant from item 4, and the porosity from Eq. 29. Use a value of RT equal to 2.5×10^{10} cm²g/s²mole. The resulting storage coefficient will be in units of cm⁻¹.

The storage coefficient and gas conductivity can be directly incorporated into groundwater flow models. The only other items that need to be addressed are boundary conditions. Prescribed flow boundaries and impermeable boundaries are directly analogous to groundwater flow conditions: one simply specifies flow rates in units of length cubed per time (e.g., cm³/s). Prescribed head boundaries need to be replaced with prescribed pressure boundaries.

CASE HISTORY: MIDWAY LANDFILL, KENT, WASHINGTON

A case history is presented in this section to further illustrate the methodology for using groundwater flow models to evaluate the design of vapor extraction systems. The motivation for including the case history is to illustrate the details of the approach. The presentation is divided into two parts. In the first part, the Theis solution for groundwater flow is used to develop a preliminary design for a gas extraction well. In the second part, the results of field extraction tests are analyzed and the effectiveness of the gas extraction well is evaluated.

The case history is based on the Midway Landfill in Kent, Washington. The landfill is located in an abandoned gravel quarry just south of Seattle. A generalized cross section through the landfill is illustrated on Fig. 2 [Hart-Crowser (1986)]. The site stratigraphy can be summarized as a three-layer system. The top layer consists of low-permeability glacial till. This till overlies a thick deposit of sand and gravel. Beneath the sand and gravel is a layer of clay and clayey-silt. The approximate location of the groundwater table is at the top of the clay unit.

Methane gas produced by the decomposition of organic materials within the landfill had been detected in the immediate vicinity of the landfill at concentrations above the lower explosive limit. An extensive gas monitoring program was undertaken in the fall and winter of 1985 by the Washington Department of Ecology (WDOE) and the City of Seattle to evaluate the extent of methane migration. The program involved installing and monitoring more than 80 subsurface gas probes and monitoring gas concentrations in homes and businesses in the vicinity of the landfill. These activities indicated that potentially explosive conditions were present over distances greater than 500 m from the landfill site. The most extensive migration occurred to the east of the landfill. Homes and business were evacuated in response to these potentially explosive conditions, some for periods in excess of several months.

Two general activities to alleviate the problems associated with the methane migration were undertaken in late 1985 and early 1986. The first activity was to install a methane collection system on the landfill to prevent additional gas from leaving the site. This on-site system was intended to stop the gas source but not to clean areas in which gas had previously migrated.

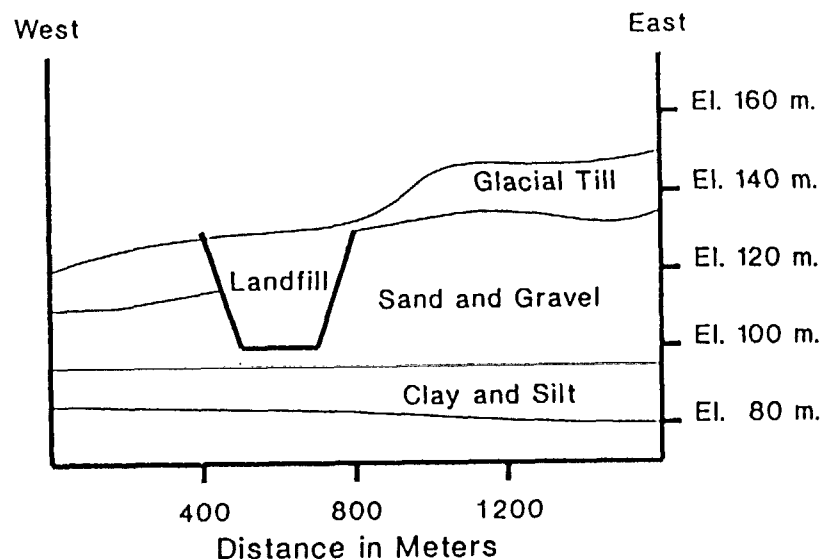


FIG. 2. Generalized Geologic Cross Section Through Midway Landfill

The second activity was to install several off-site extraction wells east of the landfill to reduce the methane concentrations in these areas. Groundwater flow models were used to help evaluate the design of both the on-site and off-site methane control systems. The evaluations pertaining to the off-site system are described below.

PRELIMINARY DESIGN OF OFF-SITE EXTRACTION WELLS

The WDOE decided to install several off-site extraction wells in the neighborhoods east of the landfill in an effort to reduce methane concentrations in the vicinities of homes that had been evacuated. The approach adopted by the WDOE was to extract the methane by using a relatively small number of large extraction wells. The off-site wells were to be completed in the sand and gravel formation immediately beneath the surface till and were to be approximately 100 ft deep.

Extraction systems were available that were capable of delivering 115 L/s of gas (250 cu ft/min) when operating against a vacuum equal to approximately 1 m of water (0.1 atmosphere). The Theis solution for groundwater flow was used to predict pressure drawdowns within the extraction well as a function of extraction rate to determine if these systems would be suitable for the Midway site. The steps included in this evaluation are summarized below:

1. Gas viscosity. Monitoring activities had indicated that the subsurface gas composition near the proposed site for the extraction well was approximately 50% methane and 50% air, by volume. The viscosity of methane is 1.1×10^{-4} g/cm/s and the viscosity of air is 1.8×10^{-4} g/cm/s. The viscosity for the gas

TABLE 5. Predicted Pressure Drawdowns Within Extraction Well as Function of Time for Extraction Rate Equal to 115 L/s

Time after start-up (1)	Pressure drawdown (cm of water) (2)
10 min	43
100 min	52
1,000 min	62
7 days	71
70 days	80

mixture is given by Eq. 27: $\mu_{\text{mix}} = 0.5(1.1 \times 10^{-4}) + 0.5(1.8 \times 10^{-4}) = 1.45 \times 10^{-4}$ g/cm/s.

2. Gas density. The density of methane is approximately 0.7×10^{-3} g/cm³ and the density of air is approximately 1.3×10^{-3} g/cm³. The resulting density of the gas mixture is therefore 1.0×10^{-3} g/cm³.

3. Permeability. Soil samples collected at the time the gas monitoring probes were installed were available for grain size analyses. The average D_{15} grain size from 47 samples collected from the sand and gravel formation was approximately 0.1 mm. Incorporating this value into Eq. 35 gives an order-of-magnitude estimate for permeability equal to 10 darcies (1×10^{-7} cm²).

4. Gas conductivity. The gas conductivity can be estimated using Eq. 30: $K = \rho g k / \mu = 1 \times 10^{-3}(980)1. \times 10^{-7} / (1.45 \times 10^{-4}) = 7 \times 10^{-4}$ cm/s.

5. Molecular weight. The molecular weights for methane and air are 16 g/mole and 28 g/mole, respectively. The molecular weight for the mixture is given by Eq. 28: $W_m = 0.5(16) + 0.5(28) = 22$ g/mole.

6. Storage coefficient. The storage coefficient, assuming a value for porosity equal to 0.15, is given by Eq. 18: $S_s = \rho n W_m / RT = 0.15(980)22 / (2.5 \times 10^{10}) = 1.3 \times 10^{-7}$ cm⁻¹.

The gas conductivity and storage coefficient values can be directly incorporated in the Theis equation to estimate pressure drawdowns:

$$h - h_0 = \frac{Q}{4\pi K b} W(u) = \frac{Q W(u)}{4(3.14)(0.0007)(2,500)} \dots \dots \dots (36)$$

where b = the thickness of the unsaturated zone (L); Q = volumetric flow rate (L³/T); $W(u)$ = well function (dimensionless); $h - h_0$ = drawdown (L); and $u = r^2 S_s / 4Kt$.

The drawdowns calculated with Eq. 36 will be in centimeters of gas. To convert to equivalent centimeters of water, it is necessary to multiply the calculated drawdown by the specific gravity of the gas, which is approximately 0.001 for a gas density of 1×10^{-3} g/cm³. Estimated pressure drawdowns within a 15-cm diameter extraction well operating at an extraction rate of 115 L/s (250 cu ft/min) are presented in Table 5. After 70 days of pumping, the estimated drawdown within the extraction well is approximately 80 equivalent cm of water. This estimate suggested that the extraction system capable of delivering 120 L/s against 1 m of vacuum would be suitable for the Midway site.

EVALUATION OF FIELD EXTRACTION TESTS

An extraction well was installed east of the Midway Landfill in January 1986. The construction of the well, based in a part on the preliminary design evaluations described above, is illustrated on Fig. 3. A pumping test was performed on the extraction well in February 1986 to evaluate the overall performance of the system. The test involved measuring the pressure drawdowns in the extraction well and in nearby observation probes as a function of time while the extraction well was pumped at a constant rate.

The pressures within the well were measured with a mercury manometer. The construction of the extraction well allows the pressures to be measured at the bottom of the well and at the ground surface. The pressure at the bottom of the well during the test was approximately -100 cm of water and the pressure at the top was approximately -95 cm of water (negative values denote vacuum). The extraction rate during the test, which was estimated by measuring the velocity within the header pipe at the ground surface, fluctuated between 100 and 110 L/s (215-235 cu ft/min). The gas temperature was 11° C (52° F).

The cluster of observation probes, which is illustrated on Fig. 3, contains shallow, intermediate, and deep probes. The pressures within the probes were measured with an electronic pressure transducer. The transducer provides continuous digital readings accurate to about 0.05 cm of water. The majority of the pressure measurements were made in the intermediate probe, which is screened between the depths of 40 and 60 ft. The measurements were

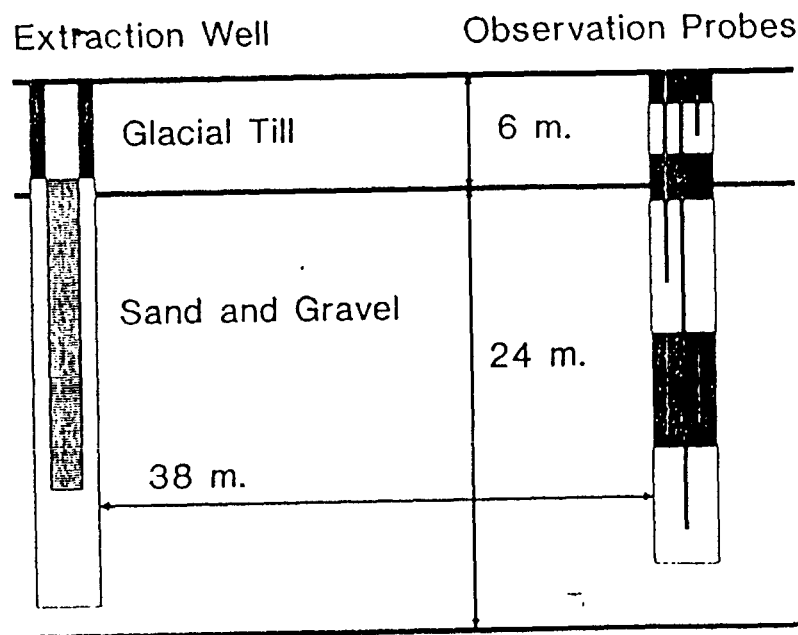


FIG. 3. Geometry of Extraction Well and Gas Probes used in Field Extraction Test

TABLE 6. Summary of Field Test Data and Evaluations; All Pressures and Drawdowns are in Equivalent Centimeters of Water

Time (min.) (1)	Observed pressure (2)	Corrected pressure (3)	Corrected drawdown (4)	Calculated drawdown (5)
0	-7.37	-7.37	0.00	0.00
1	-7.29	-7.42	0.05	0.00
2	-7.26	-7.45	0.08	0.00
3	-7.26	-7.42	0.05	0.02
5	-7.32	-7.40	0.03	0.15
6	-7.44	-7.55	0.18	0.25
7	-7.62	-7.75	0.38	0.43
9	-7.87	-8.03	0.66	0.74
11	-8.20	-8.39	1.02	1.04
14	-8.74	-8.97	1.60	1.52
18	-9.35	-9.66	2.29	2.16
21	-9.86	-10.19	2.82	2.60
26	-10.36	-10.80	3.43	3.22
31	-10.92	-11.43	4.06	3.81
41	-11.76	-12.42	5.05	4.82
46	-12.07	-12.81	5.44	5.23
61	-12.90	-13.90	6.53	6.35
101	-13.69	-15.32	7.95	8.00
166	-14.07	-16.74	9.37	9.14
306	-13.82	-17.48	10.11	10.16

made for approximately five hours. The observed pressures within the intermediate probe are listed in Table 6 and are illustrated on Fig. 4. The shallow probe, which is screened in the silty-sand confining materials, responded more slowly than the intermediate probe. The slower response is expected because of the lower permeability of the materials in which it is completed. The deep probe responded as quickly as the intermediate, but the total drawdown during the test was about 10% less than the drawdown in the intermediate probe. The smaller response of the deep probe may be due to its vertical position relative to the extraction well. The deep probe is completed below the bottom of the extraction well.

An important aspect of the extraction test is that pressures are measured relative to atmospheric pressure. Atmospheric pressure is seldom constant and therefore the observed drawdowns need to be corrected for variations in barometric pressures. During the 24 hours preceding the extraction test, the barometric pressures steadily increased by approximately 15 cm of water. The pressures steadily dropped by approximately 3 cm of water during the test.

Pressures were measured during the test in several gas probes outside the zone of influence of the extraction well to gain information on the effects of barometric pressures. As an example, Table 7 lists pressures in a gas probe approximately 150 m from the extraction well during the extraction test. This probe is screened over approximately the same depth as the intermediate observation probe shown on Fig. 3. The pressures within the probe clearly show the effects of variations in barometric pressure.

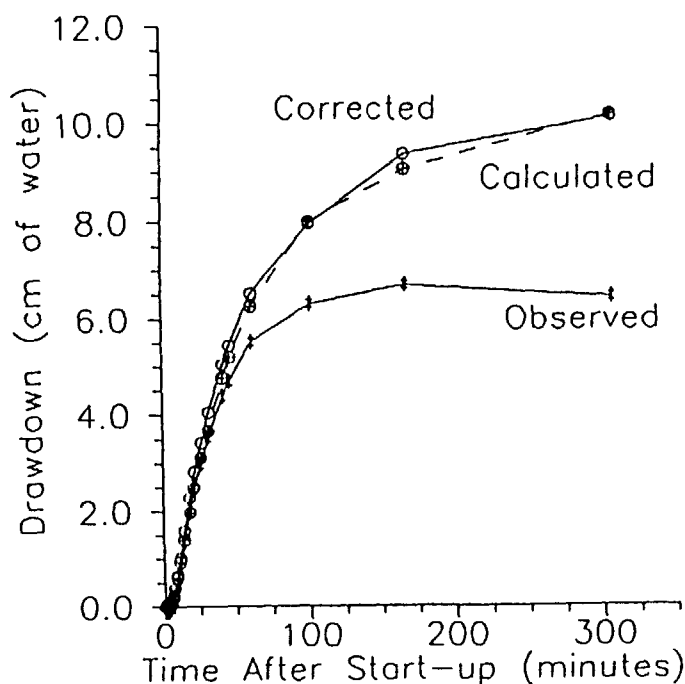


FIG. 4. Observed, Corrected, and Calculated Pressure Drawdowns for Field Extraction Test

The atmospheric high-pressure system that moved into the Midway area the day before the extraction test caused negative gauge pressures in the gas probes prior to pumping. Compensation can be made for these barometric effects by subtracting the gauge pressures that would be observed without pumping from the gauge pressures that were observed with pumping. The gauge pressures that would be observed without pumping can be predicted from measurements made in probes outside the extraction well's zone of influence. The corrections for barometric effects can be estimated by linearly interpolating the values in Table 7. This process results in the following corrections:

$$P_{cor} = P_{obs} - .016t \quad \text{for } t < 150 \text{ minutes} \quad (37a)$$

TABLE 7. Gas Pressures Used to Correct for Barometric Effects—Probe GP-50 Is Located 150 m from Extraction Well

Time after start of extraction test (min) (1)	Pressure in gas probe GP-50 (cm of water) (2)
0	-9.50
150	-7.11
300	-6.04

$$P_{cor} = P_{obs} - 2.4 - .007t \quad \text{for } t > 150 \text{ minutes} \quad (37b)$$

where P_{cor} is the corrected pressure in equivalent centimeters of water and P_{obs} is the observed pressure in centimeters of water. Time $t = 0$ denotes the beginning of the test. The corrected pressures for the observation probe are included in Table 6 and Fig. 4.

A plot on logarithmic scales of the corrected drawdowns from Table 5 versus time indicates that the system responds as predicted by the Theis solution for the first 200 min of the test. The estimated gas conductivity from this portion of the test is 6.2×10^{-4} cm/s. This value was calculated using a match point of $W(u) = 1.2$; $u = 0.25$; $h - h_w = 5$ cm; and $t = 50$ min. The distance to the observation probe is 38 m (125 ft) and the extraction rate is 105 L/s (225 cu ft/min). In terms of permeability, this corresponds to a value of 9.2 darcies, which is remarkably close to the value of 12.5 darcies estimated from grain size analyses. The close correspondence is more likely an exception than a rule.

After 200 min, the observed drawdowns were less than the drawdowns predicted using the Theis solution. This discrepancy is likely due to leakage of air through the till confining unit shown on Fig. 3. The leaky-aquifer solution developed by Hantush (1956) can be used to incorporate the effects of air intrusion. The permeability of the confining unit can be estimated by matching the observed drawdowns with curves developed by Hantush (1956). A permeability of 0.2 darcies for the confining unit results a good fit to the data collected at the Midway site. The calculated drawdowns included in Table 6 and Fig. 4 are based on permeability for the confining unit equal to 0.2 darcies and permeability for the sand and gravel formation equal to 10 darcies. Except for the first three or four data points, the overall fit is quite good. It should be noted that the early data are close to the precision of the pressure transducer used to make the measurements.

The results of the extraction test were used to predict the performance of the extraction well over times and distances greater than those evaluated during the test. An analysis using the Hantush solution indicates that if the extraction well operates at 100 L/s, the steady-state drawdown at 150 m (500 ft) will be approximately 1 cm of water and steady-state conditions will be achieved after approximately 100 hours of pumping. These results, which were used to estimate a radius of influence for the well equal to 150 m, are based on the assumption that the geometric and material properties of the flow system determined during the pumping test can be extrapolated over an area much larger than actually tested. Boring logs from gas probes in the vicinity indicates that such an extrapolation is reasonable.

CONCLUSIONS

The conclusions that can be developed are summarized below:

1. The effects of slip flow are negligible for gas transport in silts, sands, and gravels under the pressure and temperature conditions typical of vapor extraction systems. An equation of motion with the same form as Darcy's law can therefore be used to model gas flow.
2. The differential equation governing gas transport in porous media is non-linear because gas density is a function of gas pressure. However, if the differ-

ence in gas pressure between any two points in the flow field is less than approximately 0.2 atmospheres, the linear differential equation developed to model groundwater flow gives a good approximation when applied to gas flow. The approximation is within 1% of the exact solution under these pressure conditions. Most vapor extraction systems will operate in this range of pressures.

3. For pressure differences greater than approximately 0.5 atmospheres, the groundwater flow equation gives a poor approximation to the gas flow equation. A linear differential equation written in terms of gas pressure squared (Eq. 24) will still provide a good approximation to the nonlinear gas transport equation under these conditions.

4. The storage coefficient term for gas transport is a function of molecular weight, porosity, and temperature. It can be determined without relying upon field tests.

5. The results of the field extraction tests illustrate the importance of correcting field data for the effects of fluctuations in barometric pressures.

6. Data collected from field extraction tests can be analyzed in a manner analogous to groundwater pumping tests. Analytical solutions for modeling groundwater flow in confined and leaky aquifers give good approximations to gas flow phenomena.

ACKNOWLEDGMENTS

The gas extraction tests described in the paper were completed while the author was a Project Engineer at Hart-Crowser, Inc., Seattle, Washington. The work was performed as part of a contract between Black and Veatch and the Washington Department of Ecology. Pete Kmet, an engineer with the Washington Department of Ecology, was instrumental in completing the extraction tests.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

- b = thickness of unsaturated zone (L);
- c = empirical constant relating soil grain and pore sizes;
- D_1 = $\mu n/k$;
- D_{15} = grain size parameter;
- $erf()$ = error function;
- F = molar flux (mol/L²/T);
- g = gravitational acceleration (L²/T);
- h = fluid head (L);
- h_o = initial fluid head (L);
- K = hydraulic conductivity (L/T);
- k = permeability of soil (L²);
- m = number of gas components in mixture;
- n = porosity of soil;
- n_a = air porosity;
- n_T = total porosity;
- P = gas pressure (M/L/T²);
- P_1 = gas pressure at extraction well or boundary (M/L/T²);
- P_{cor} = pressures corrected for barometric effects (M/L/T²);
- P_o = initial gas pressure (M/L/T²);
- P_{obs} = observed gas pressure (M/L/T²);
- Q = volumetric flow rate (L³/T);
- q = specific discharge (L/T);
- R = gas constant (L²/degree K/T²/mole);
- r = average pore radius (L);
- S = degree of saturation;
- S_s = specific storage (L⁻¹);
- T = gas temperature (degree K);
- t = time;
- u = dimensionless time used in Theis well function;
- V_m = mean molecular velocity (L/T);
- W_m = molecular weight (M/mol);
- $(W_m)_i$ = molecular weight of component i ;
- $W(u)$ = Theis well function;
- X_i = mol fraction of component i ;
- x = distance;
- Y = $(D_1/P_o)(x/2t)$;
- Z = elevation (L);
- μ = gas viscosity (M/L/T);
- μ_{mix} = viscosity of gas mixture (M/L/T);
- μ_i = viscosity of component i (M/L/T);
- ϕ = fluid potential (L²/T²);
- ρ = density of the fluid (M/L³); and
- ρ_o = the initial gas density (M/L³).

ANALYSIS OF IN SITU VACUUM WELL PLACEMENT USING MODFLOW

BACKGROUND

The governing equation for 3-D single phase flow which is solved by MODFLOW using a finite difference method is given by

$$S, \frac{\partial h}{\partial t} = - \frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} - \frac{\partial q_z}{\partial z} \quad [1]$$

where the volumetric flux density in the i -direction is given by

$$q_i = - K_i \frac{\partial h}{\partial x_i} \quad [2]$$

These equations describe saturated groundwater flow subject to certain assumptions regarding decoupling between saturated and unsaturated zones. The same equations may be used to simulate gas flow in the unsaturated zone under the assumption that: 1) gradients in gas phase density are small compared to the divergence of the gas velocity; 2) effects of gas pressure gradients on water flow by capillary effects are disregarded, e.g., water table upwelling is ignored; and 3) gravitational gas flow is assumed negligible compared to pressure effects. Under these conditions, [1] and [2] will describe gas flow in the unsaturated zone when q_i is taken as the volumetric flux density of gas and other variables are defined as follows

$$h = P/\rho_w g \quad [3]$$

$$K_i = \rho_w g k_{a_i}/\eta_a \quad [4]$$

$$S_s = \mathcal{M} \rho_w g \phi_a / \rho_a R T \quad [5]$$

where P is the gauge gas phase pressure [$F L^{-2}$], ρ_w is the density of water [$M L^{-3}$], g is gravitational acceleration [$L T^{-2}$], k_{a_i} is gas permeability in the i -direction [L^2], η_a is the dynamic viscosity of the gas phase [$F T L^{-2}$], \mathcal{M} is the molecular weight of gas [$M \text{ mol}^{-1}$], ϕ_a is the gas filled porosity [$L^3 L^{-3}$], ρ_a is the density of gas [$M L^{-3}$], R is the gas constant [$F L \text{ mol}^{-1} \text{ deg}^{-1}$] and T is Kelvin temperature [deg].

In equation [3], h represents the gas pressure expressed in units of equivalent water height. For example, an absolute gas pressure of 0.8 atm or equivalently a vacuum of 0.2 atm corresponds to a gas pressure head of $h = -2$ m. In equations [4] and [5], K_i and S_s may be referred to as the gas conductivity and specific storage, respectively. It should be noted that alternative means of defining a gas conductivity are possible (using a different reference fluid density) so caution should be used to ensure consistent usage. In [5] it has been assumed that porous medium compressibility is negligible and gas compressibility follows the ideal gas law. For a gas-filled porosity of 0.2 at 10°C, the gas specific storage, S_s , will be approximately 0.02 m^{-1} . For steady state analyses, the value of S_s has no effect on the solution -- it only effects the time required to reach steady state conditions.

An alternative way to write [4] arises by noting that $k_{a,i} = k_{r,a} k_i$, where $k_{r,a}$ is the gas relative permeability which varies from 0 to 1 and k_i is the intrinsic permeability in the i -direction. Since intrinsic permeability is related to the saturated hydraulic conductivity, $K_{s,w,i}$, as $k_i = K_{s,w,i} \eta_w / \rho_w g$ then we may write

$$K_{a,i} = k_{r,a} K_{s,w} / \eta_{r,a} \quad [6]$$

where $\eta_{r,a} = \eta_a / \eta_w$. Relative permeability, $k_{r,a}$, will vary from zero when ϕ_a is zero to 1 when ϕ_a is equal to the total porosity, ϕ . The sensitivity of gas relative permeability to gas filled porosity is rather mild at low water contents such that relative permeability generally decreases in a manner roughly proportional to the gas saturation, ϕ_a / ϕ , for gas saturations greater than about 25%. Therefore, to first approximation, gas conductivity may be estimated from hydraulic conductivity if this is known by employing [6] with $k_{r,a} \approx \phi_a / \phi$. Vertical variations in intrinsic permeability as well as gas relative permeability could be incorporated in the numerical analysis by assigning different gas permeabilities to different layers or areal zones in the model. In practice, the most practical and reliable procedure for determining gas conductivity will be to perform an in situ gas pump test. The pump test data may be analyzed in the same fashion as conventional water pump tests using analytical methods (e.g., Theis or Jacob) or the numerical model may be used to simulate the pump test with conductivity adjusted (by hand or using an automatic algorithm) to fit the observed flow rates and/or observation well pressures.

EXAMPLE PROBLEM

A hypothetical problem was analyzed to demonstrate the use of MODFLOW for designing in situ vacuum extraction systems. The problem involves a domain 250 x 250 m in the areal plane with an unsaturated soil thickness of 20 m (Figure 1). Part of the soil surface over the central 150 x 150 m of the domain is covered with a gas impermeable material and the remainder is open to the atmosphere on an annular strip. Soil properties were assumed to be uniform over the domain with $K_x = K_y = 300 \text{ m d}^{-1}$ and $K_z = 100 \text{ m d}^{-1}$. The gas specific storage was taken to be 0.02 m^{-1} . In analysis A, three vacuum extraction wells (W-1, W-2 and W-3) were placed through the covered area and screened over the depth of 15 to 20 m. In analysis B, a fourth well (W-4), screened over the same interval, was placed at a location that would otherwise yield a stagnation point in the gas flow.

Boundary conditions. The lower boundary of the system is the upper limit of the capillary fringe (or to first approximation, the water table). This boundary is assumed initially known from observation well data and is fixed with time. The boundary condition at the bottom is no-flow. Actually, water table upwelling will occur when vacuum wells are pumped. The exact rise in the water table will be equal in magnitude and opposite in sign to the gas pressure head on the lower boundary. Therefore, if a more refined analysis is desired, the location of the lower boundary may be corrected in an iterative fashion. The simplest way to accomplish this would be to reduce the conductivity of the lower blocks in proportion to the fraction which is water-saturated (i.e., if water occupies 0.6 of the block height, reduce K by 0.6).

The lateral boundaries of the system are also treated as no flow boundaries and should be located such that this assumption is met. That is, it is desired that the lateral boundaries be far enough away from the vacuum source that negligible pressure change is propagated to the boundary. If initial simulations indicate this condition is not met, the domain size should be increased.

The upper boundary is the soil surface. Covered portions should be treated as no flow boundaries. Portions which are uncovered should be treated as constant pressure boundaries. Specifically, $h=0$ is assumed on atmospheric boundaries.

Vacuum wells are treated as normal pumping wells in MODFLOW with the total gas flow rate prescribed [$M^3 T^{-1}$]. Note that withdrawal rates have a negative sign. If the well bore vacuum is known rather than the withdrawal rate, then the latter should be guessed and several trial simulations performed until the correct flow rate is obtained. In the present case, the flow rates at wells W-1, W-2 and W-3 were each assumed to be $10,000 m^3 d^{-1}$.

Injection wells are treated as interior prescribed pressure nodes. Specifically, they are treated as nodes with a constant pressure of $h=0$ on the screened portion. Well W-4 is treated in this fashion.

Model results. Contour plots of the steady state gas pressure head distributions for problems A and B are shown in Figures 2 and 3, respectively. In designing the vacuum system, it is desired to have gas flow directed through the hydrocarbon contaminated soil with no stagnant zones. Placement, screening interval and pressure of vacuum wells; location and screening interval of intake wells; and extent of surface cover may be manipulated to achieve suitable system operating conditions. Inspection of the pressure field within the zone of contamination may be used to judge the design in an ad hoc fashion. A more quantitative and accurate approach would be to perform an analysis of travel time distributions through the plume with the objective of designing the system to minimize the mean travel time and the travel time variance. Such an analysis could be performed using a program such as GWPATH which interfaces with MODFLOW to compute travel times on selected streamlines. Starting points for the travel time analysis should be selected on start at the plume boundary and at injection wells if they occur such that streamtubes of equal total flow are analyzed.

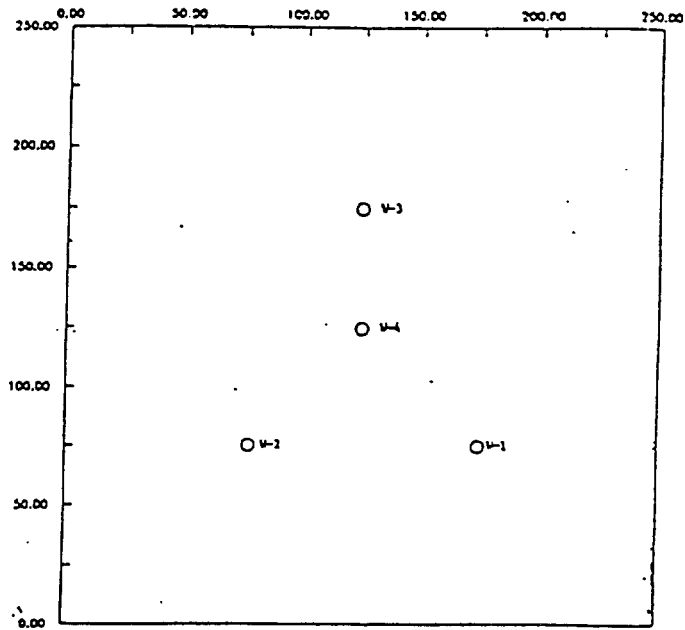


Figure 1. Areal view of hypothetical gas venting problem.

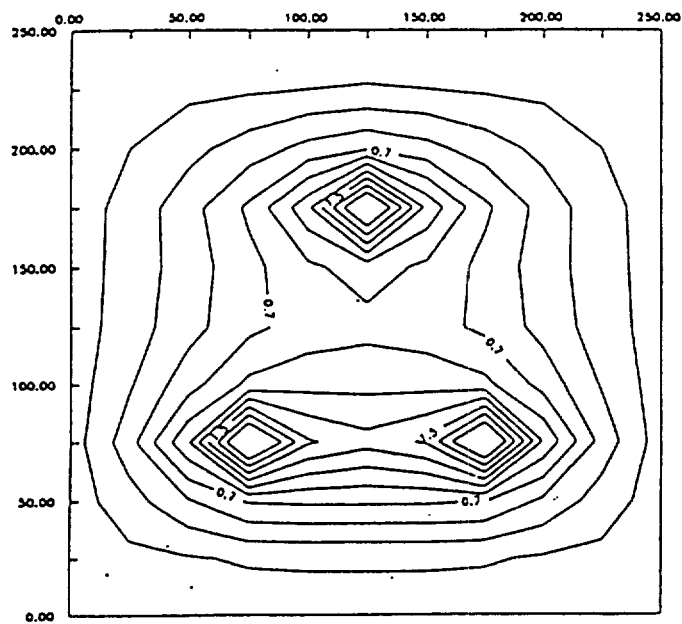


Figure 2. Contour plot of gas pressure heads (h , meters) without injection well W-4.

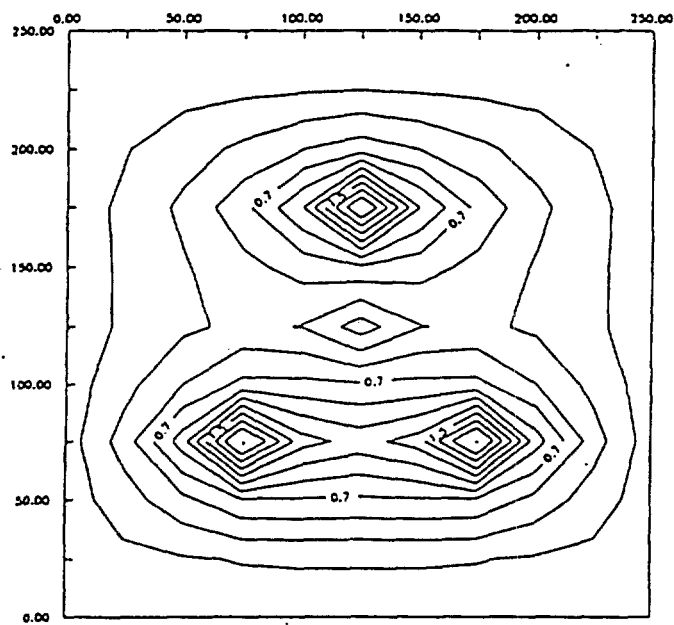


Figure 3. Contour plot of gas pressure heads (h , meters) with injection well W-4.

SECTION 4

Determination of Radius of Influence for Soil Vapor Extraction and Air Sparging.

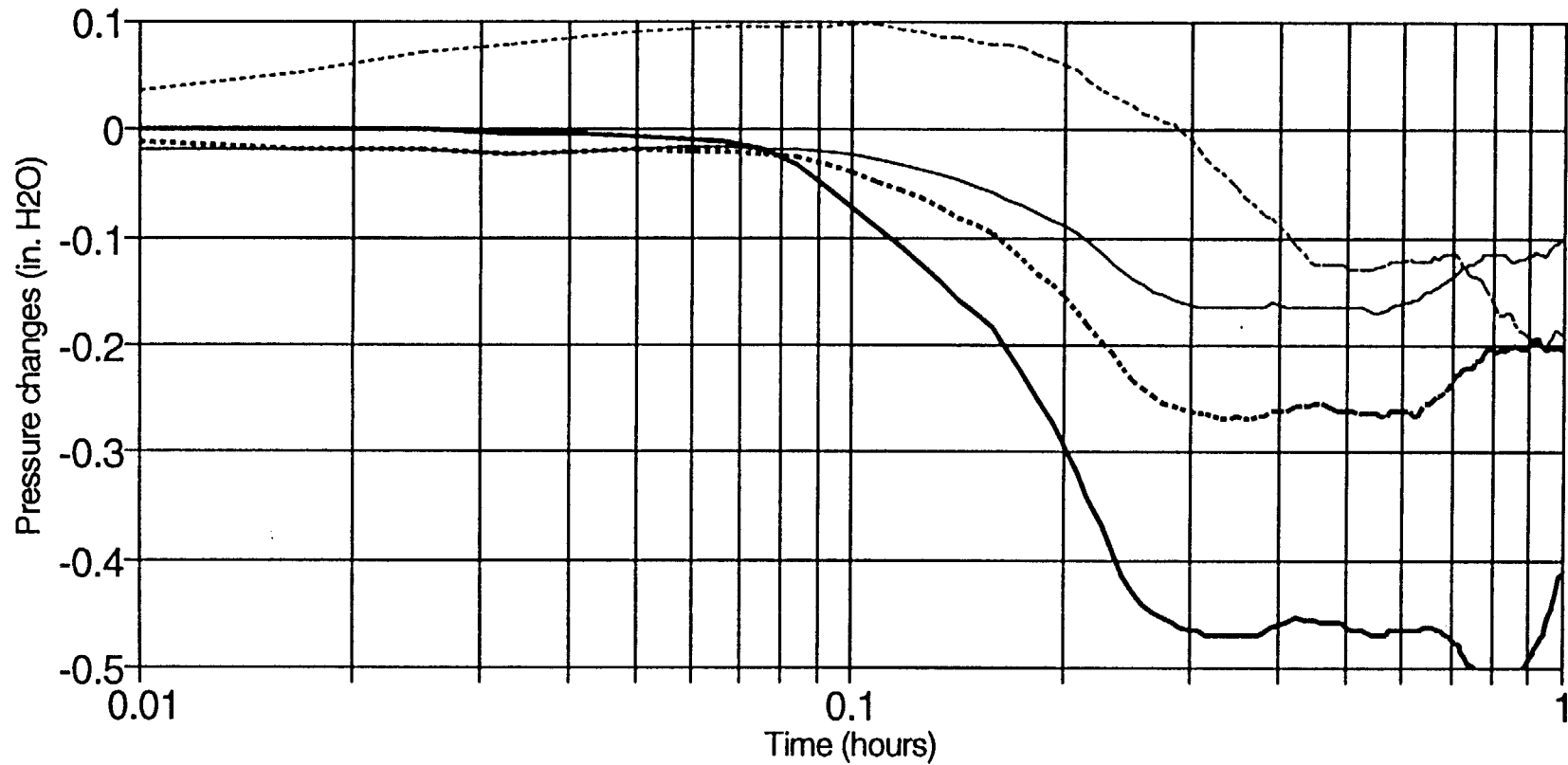
ESTIMATE OF SOIL VAPOR EXTRACTION RADIUS OF INFLUENCE

One of the primary reasons for performing the pilot study was to determine the radius of influence of the soil vapor extraction well PR-1. All flow rates tested showed a pressure change out to the farthest well. The 150 CFM test will be used to determine the radius of influence, because it is the well design flowrate for the full system.

The normal method to determine the maximum radius of influence is to plot the pressure drops from the pilot study on a semi-log plot. The pressures drops used for this plot are the measured during the initial stages of the pilot after a steady state condition was reached. Figure 1. plots the pressure changes measured in each observation well during the pilot study. The pressure changes stabilized after about one half hour of operation and these changes were then plotted on a semi-log plot with distance vs. pressure change. The Minimum pressure used to determine the maximum pressure change was 0.1 inches of water pressure. The Plot was extended to the point of 0.1 inches of pressure change and the Maximum radius of influence that could be interpreted for the pilot study would be a radius of 160 feet. The plot was also extended until the pressure change was zero and the associated radius of influence was approximately 260 feet. This plot is Figure 2.

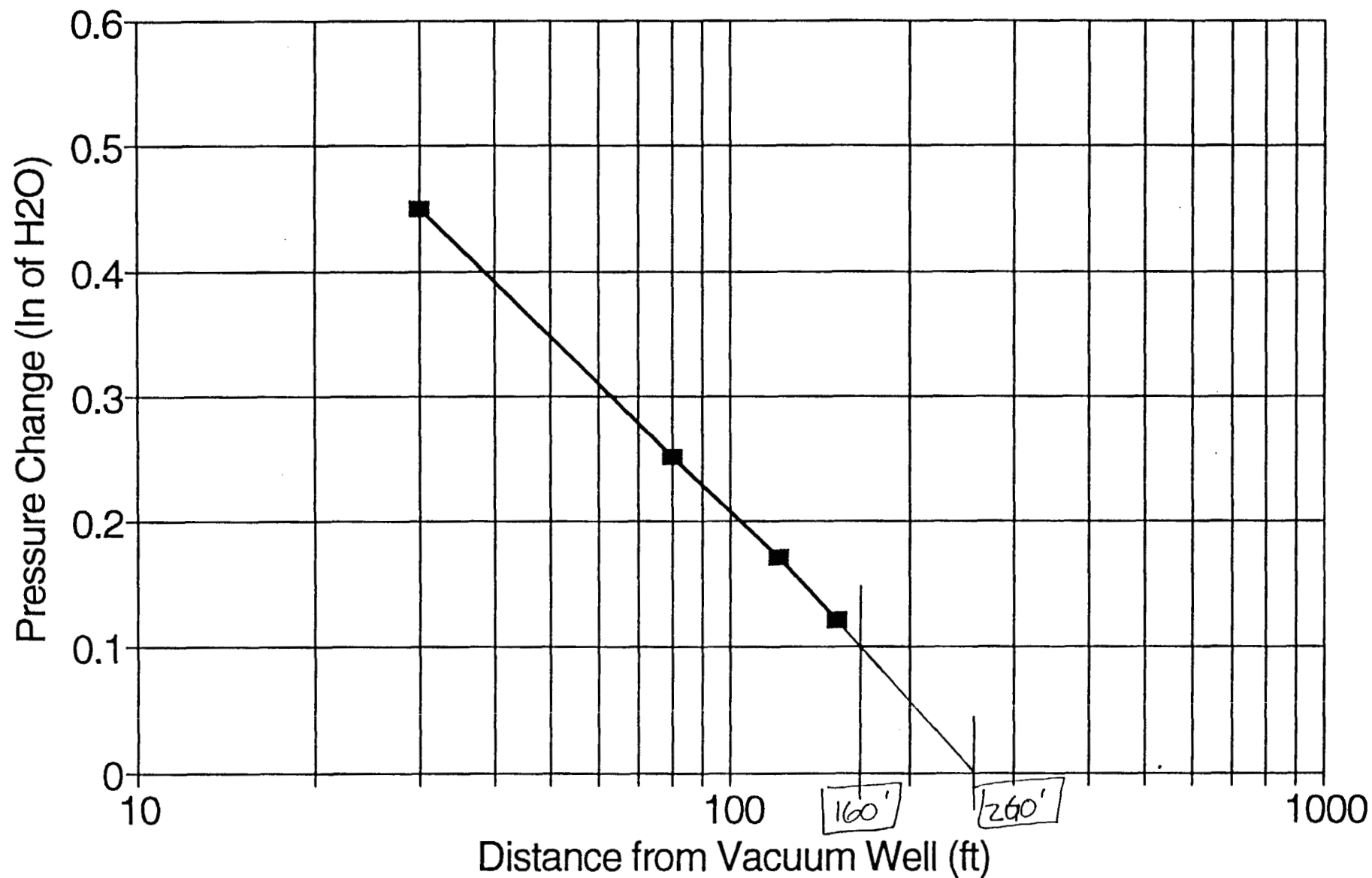
The radius of influence used for the full scale design was 120 feet. The use of this radius gives a factor of safety to ensure that the entire area is affected by the soil vapor extraction system and all the vapors from the air sparging system will be captured.

Figure 1. Air Pressure Changes 150 cfm
Soil Vapor Extraction Pilot Study



— WT-17(31') WT-13(82') — OW-1(117') OW-2(150')

Fig. 2 150 SCFM Pilot Study
Soil Vapor Extraction



ESTIMATE OF RADIUS OF INFLUENCE FOR THE AIR SPARGING SYSTEM

The measured radius of influence of the air sparging pilot study varied from 87 feet to 144 feet depending upon which parameter was used. Table 1 below summarizes the Pilot Study Results.

TABLE 1. MEASURED RADIUS OF INFLUENCE

PARAMETER	RADIUS OF INFLUENCE
Water Levels	144'
Tracer Gas	87'
Oxygen Levels in Vadose Zone	87'
Carbon Dioxide Levels in the Vadose Zone	87'
Air Pressure	87'
Dissolved Oxygen	87'

The pilot system was able to effect change in the water table as far as 144' feet from the sparging well. The dissolved oxygen and vadose zone oxygen levels were raised to saturation levels, which will greatly increase the opportunity for biodegradation of the contamination in both the groundwater and the vadose zone.

The distance of 75 feet was chosen for the effective radius of influence to be used for the air sparging design. This will provide a reasonable factor of safety and will provide some overlap between adjacent sparging wells.

SECTION 5

Soil Vapor Extraction and Air Sparging Well Layout

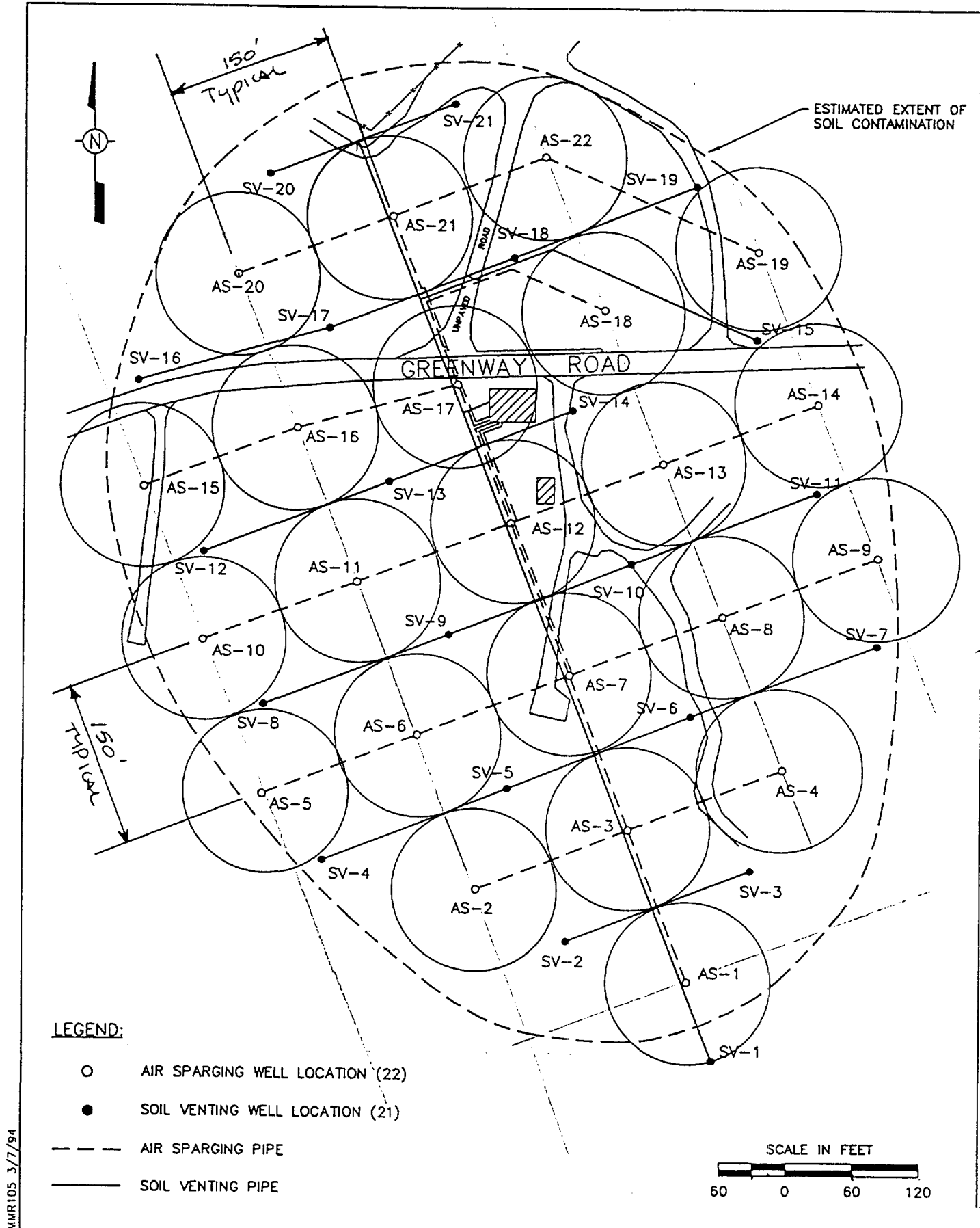
SOIL VAPOR EXTRACTION AND AIR SPARGING WELL LAYOUT

The following approach was used to determine the well layout:

- a review of the site and of the differences of radius of influences between air sparging and soil vapor extraction concluded that the 75' radius of influence for air sparging would be the controlling spacing.
- the air sparging wells were laid out on the site on a 150 by 150 foot grid (see Figure 1).
- the soil vapor extraction wells were laid out in a 150' by 180' grid (see Figure 2).

The total number of wells required was 21 soil vapor extraction wells and 22 air sparging wells.

This layout was then used as input to the computer program modflow to ensure that as the air sparging was cycled through the site that all of the "dead spots" between the wells would receive adequate ventilation and that all of the vapors created by air sparging would be captured by the soil vapor extraction system.



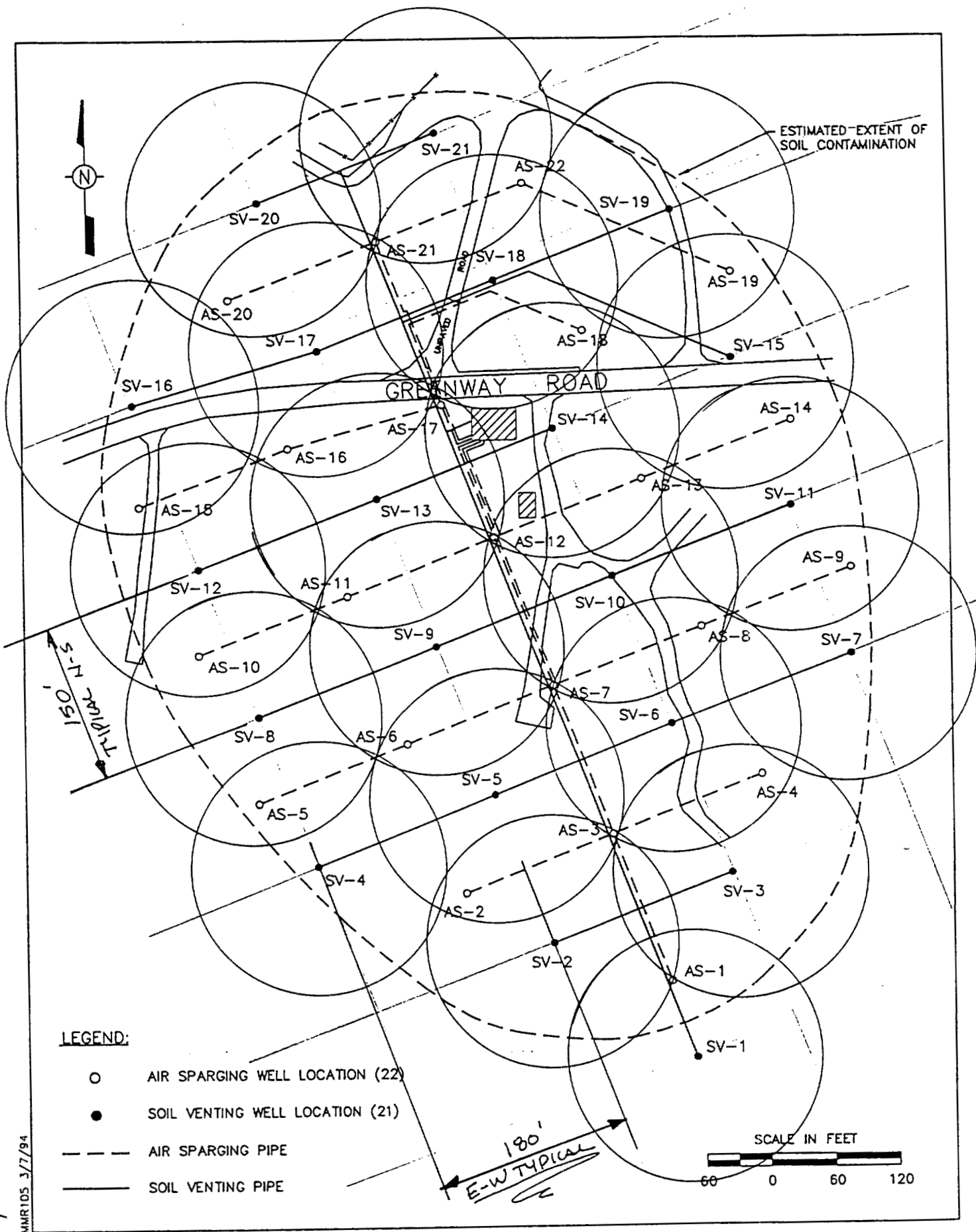


FIGURE 2.

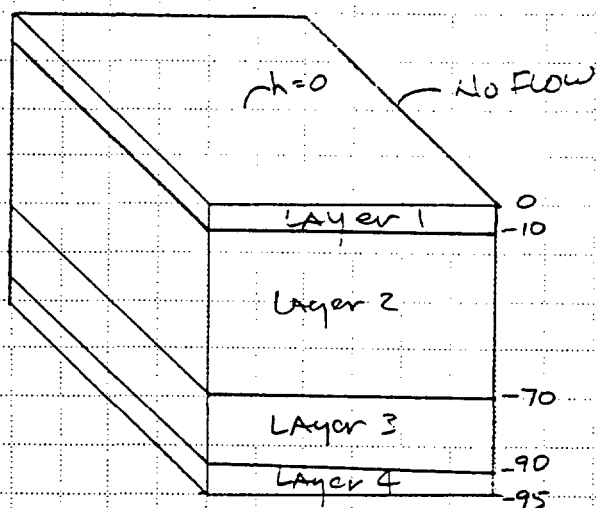
SECTION 6
MODFLOW Modeling

CALCULATION WORKSHEET

ORIGINATOR R. Hoekstra DATE 11/2/93 SHEET 1 OF
 CALC. NO. REV. NO. DATE CHECKED RC 04/20/94
 PROJECT TASK NO.
 SUBJECT

MODELING FOR THE FULL SCALE SOIL VENTING SYSTEM.

The computer model MODFLOW will be used to model the VES system. THE MODEL will consist OF THE FOLLOWING



- 100 ROW & 80 COLUMNS ON A 15' GRID.
- 4 Layers
- EACH Layer will have a NO FLOW BOUNDARY around the OUTSIDE
- Layer 1 will have a CONSTANT HEAD = 0 to MODEL ATMOSPHERIC CONDITIONS
- Layer 2 will be the layer above the Venting wells
- Layer 3 will be the layer where the Venting wells are located
- Layer 4 will be the layer where the AIR SPARGING wells are located
- THE SOIL AIR Flow Properties from the MODFLOW CALIBRATION will be used:

$$K_x = K_y = 50,910 \text{ ft/day} \quad K_z = 0.15 K_x$$

$$S_s = 0.0049 \text{ ft}^{-1}$$

- USING these UNITS THE MODFLOW Results will be in inches OF H_2O



ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR R. Hockstra DATE 11/2/93 SHEET 2 OF
CALC. NO. REV. NO. DATE CHECKED RC 04/20/94
PROJECT TASK NO.
SUBJECT

- The Flow Rates will be ^{150 CFM} 216,000 CF/DAY For the VES wells and -144,000 CF/DAY For the Air Sparging wells. ^{100 CFM}

- The signs on the flow rates are reversed so that results can be more easily plotted in Complan.

The objective of the modeling is to ensure that all of the contaminated area is included in the overall effect of the soil vapor extraction system and that the air injected during the air sparging tests will all be captured & NOT migrate off site.

Six different cases were modeled to represent the actual operation of the soil venting / Air Sparging system.

CASE 1. SOIL VENTING w/o AIR SPARGING

CASE 2. SOIL VENTING w/ AIR SPARGING IN wells AS-1, 2, 3, & 4

CASE 3. SOIL VENTING w/ AIR SPARGING IN wells AS-5, 6, 7, 8 & 9

CASE 4. SOIL VENTING w/ AIR SPARGING IN wells AS-10, 11, 12, 13 & 14

CASE 5. SOIL VENTING w/ AIR SPARGING IN wells -15, 16, 17, 18



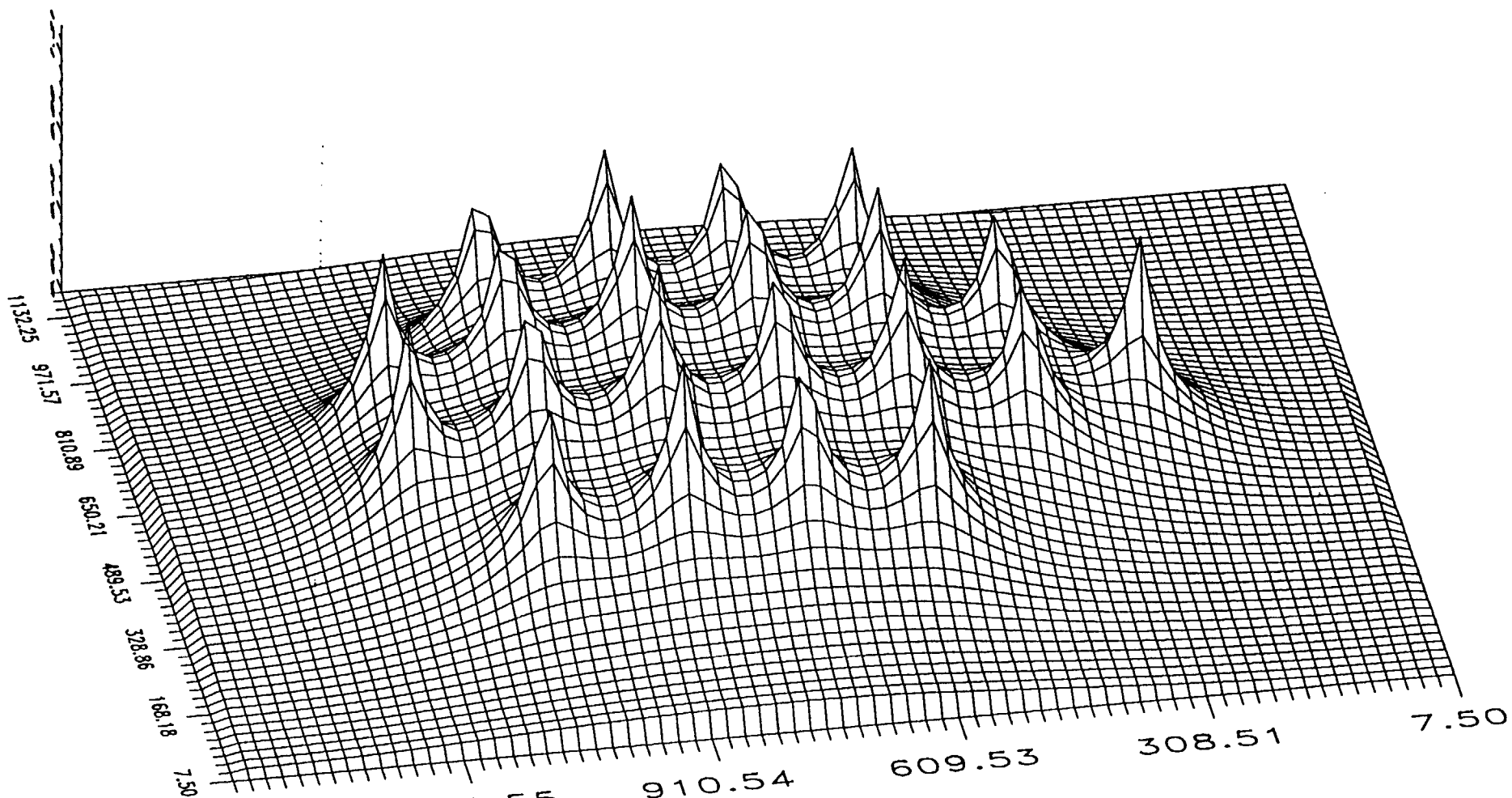
CALCULATION WORKSHEET

ORIGINATOR R. Hoekstra DATE 11/3/93 SHEET 3 OF
CALC. NO. REV. NO. DATE CHECKED RS 04/20/94
PROJECT TASK NO.
SUBJECT

CASE 60 SOIL VENTING w/ AIR SPARGING 14 Wells
AS-19, 20, 21 & 22

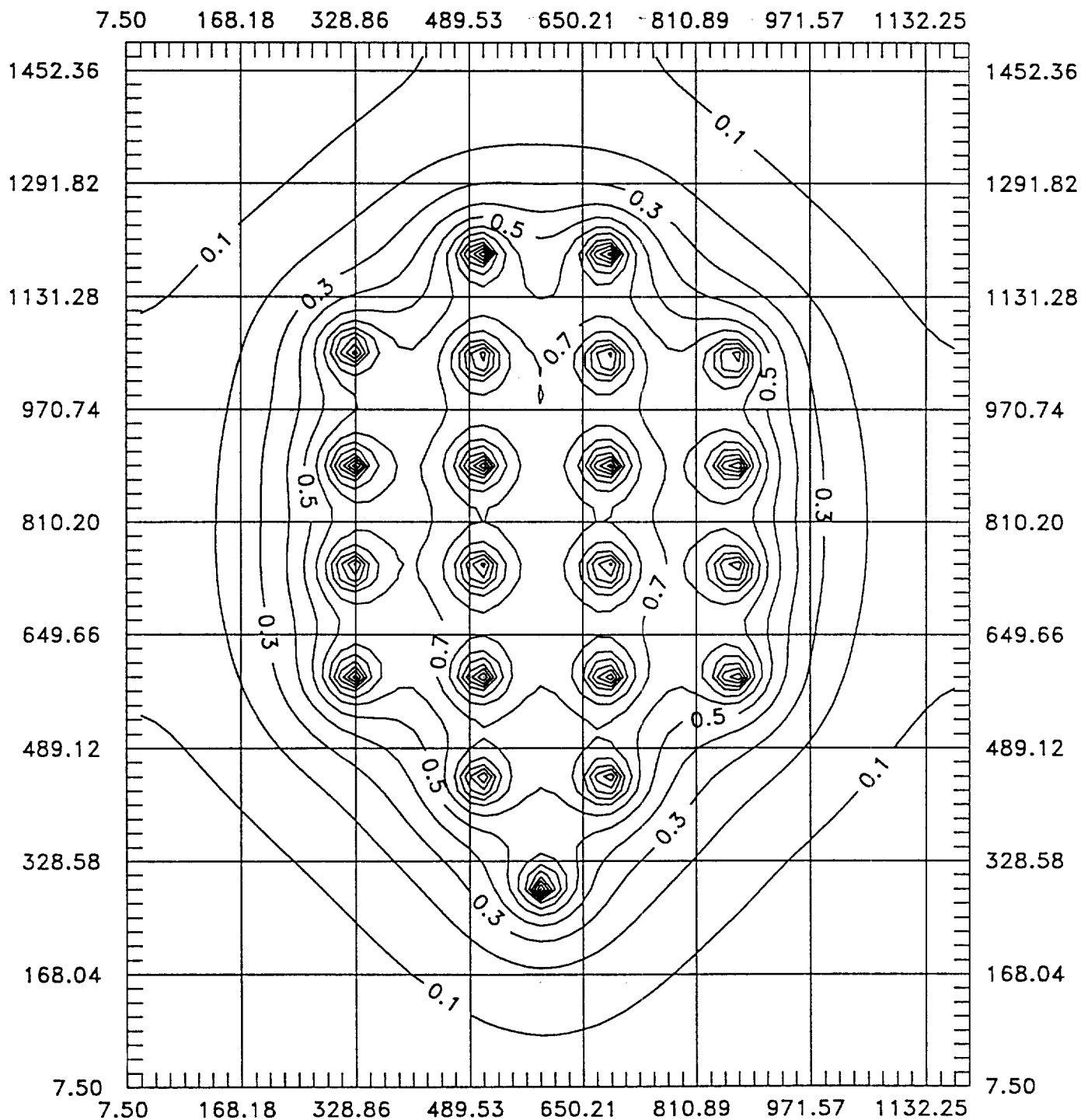
Results: Topo & 3d Plots of EACH case are
ATTACHED. IN EACH case a pressure
decrease SURROUNDED THE ENTIRE
CONTAMINATED AREA, INDICATING THAT
THE SYSTEM AS DESIGNED WILL BE
ABLE TO REMEDIATE THE SITE. ADDITIONALLY
ALL OF THE AIR SPARGING GASES WILL BE
CAPTURED BY THE SOIL VAPOR EXTRACTION
SYSTEM.

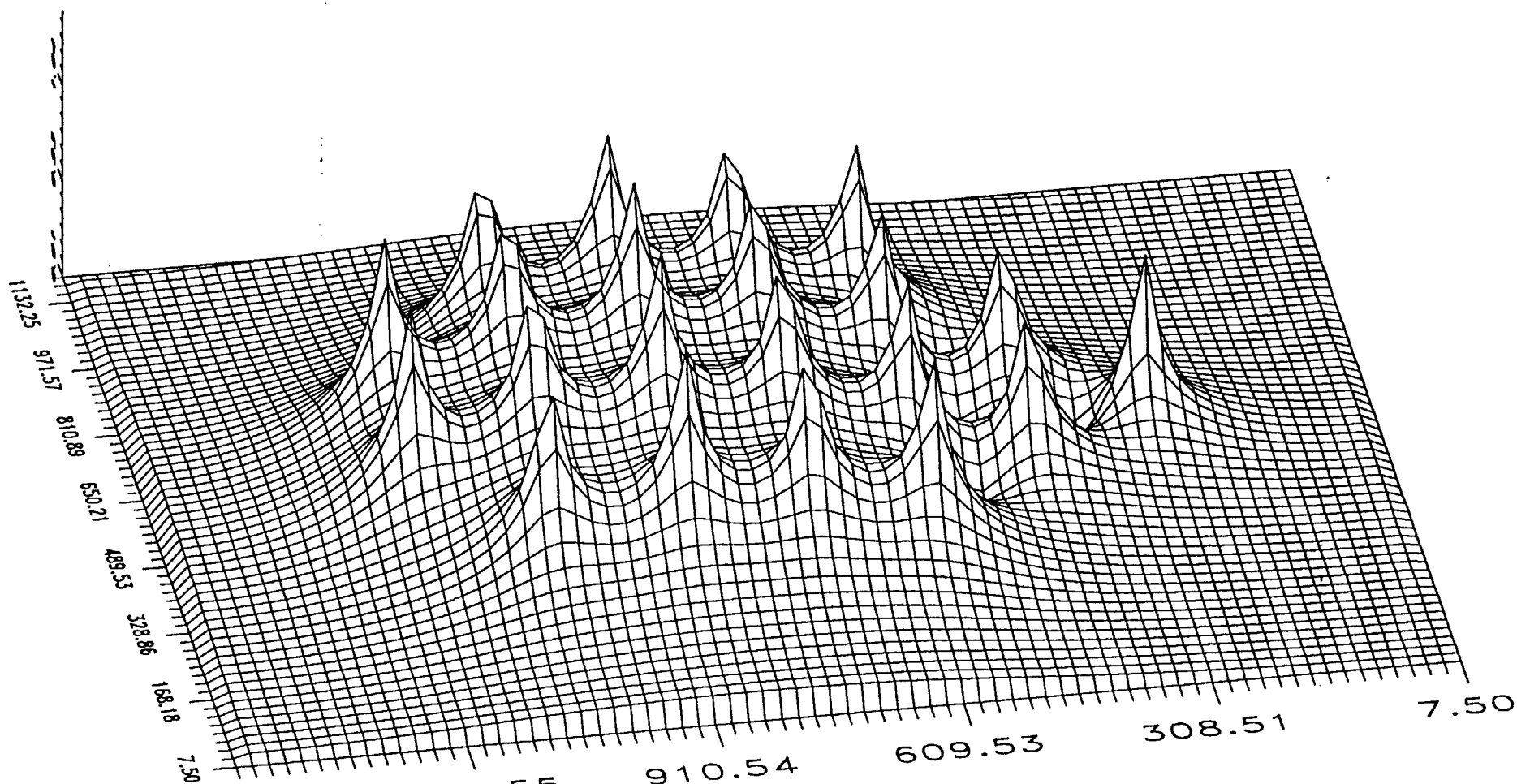




VES Pressure Dist. w/o Air Sparging

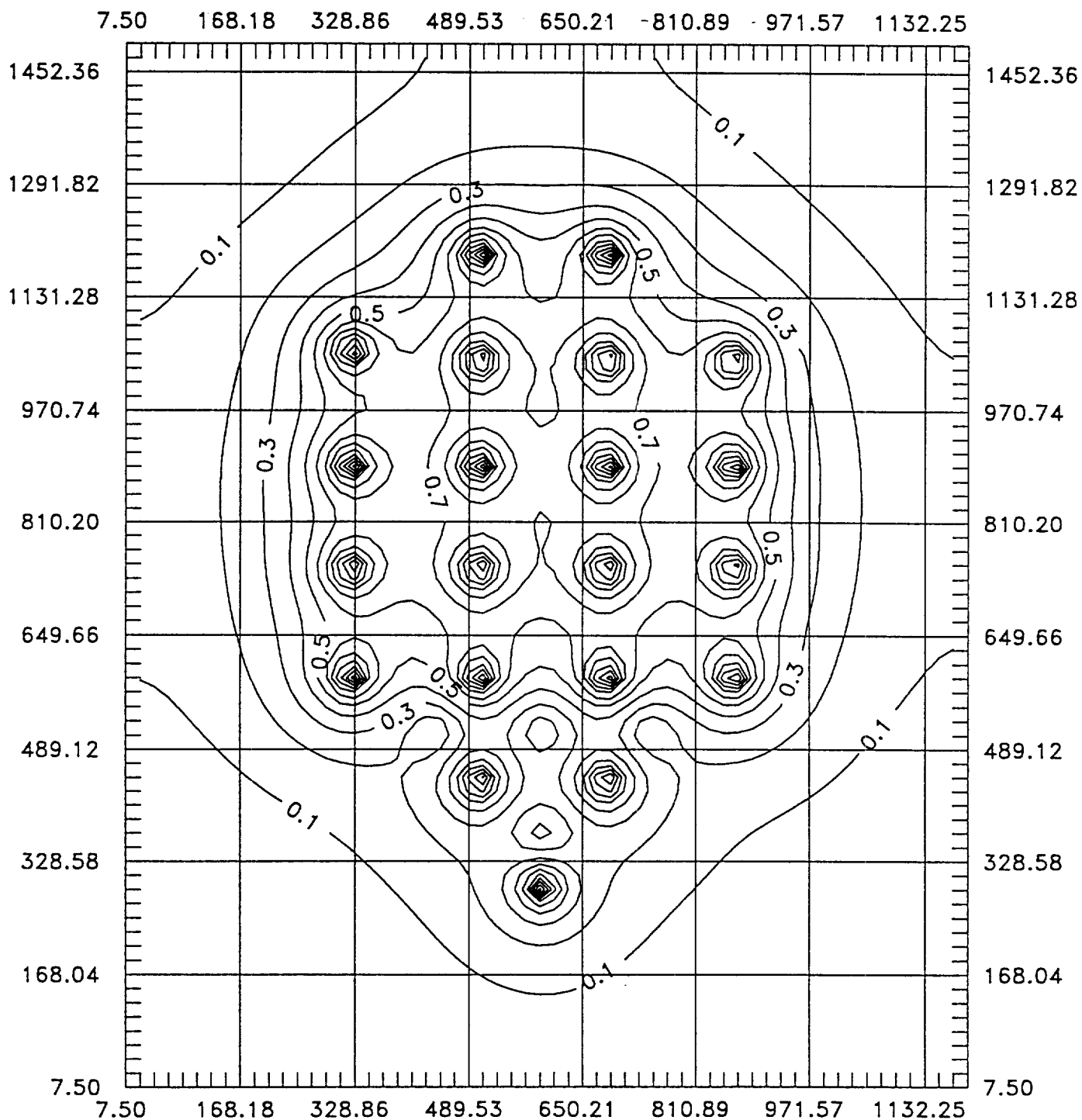
VES Pressure Dist. w/o Air Sparging

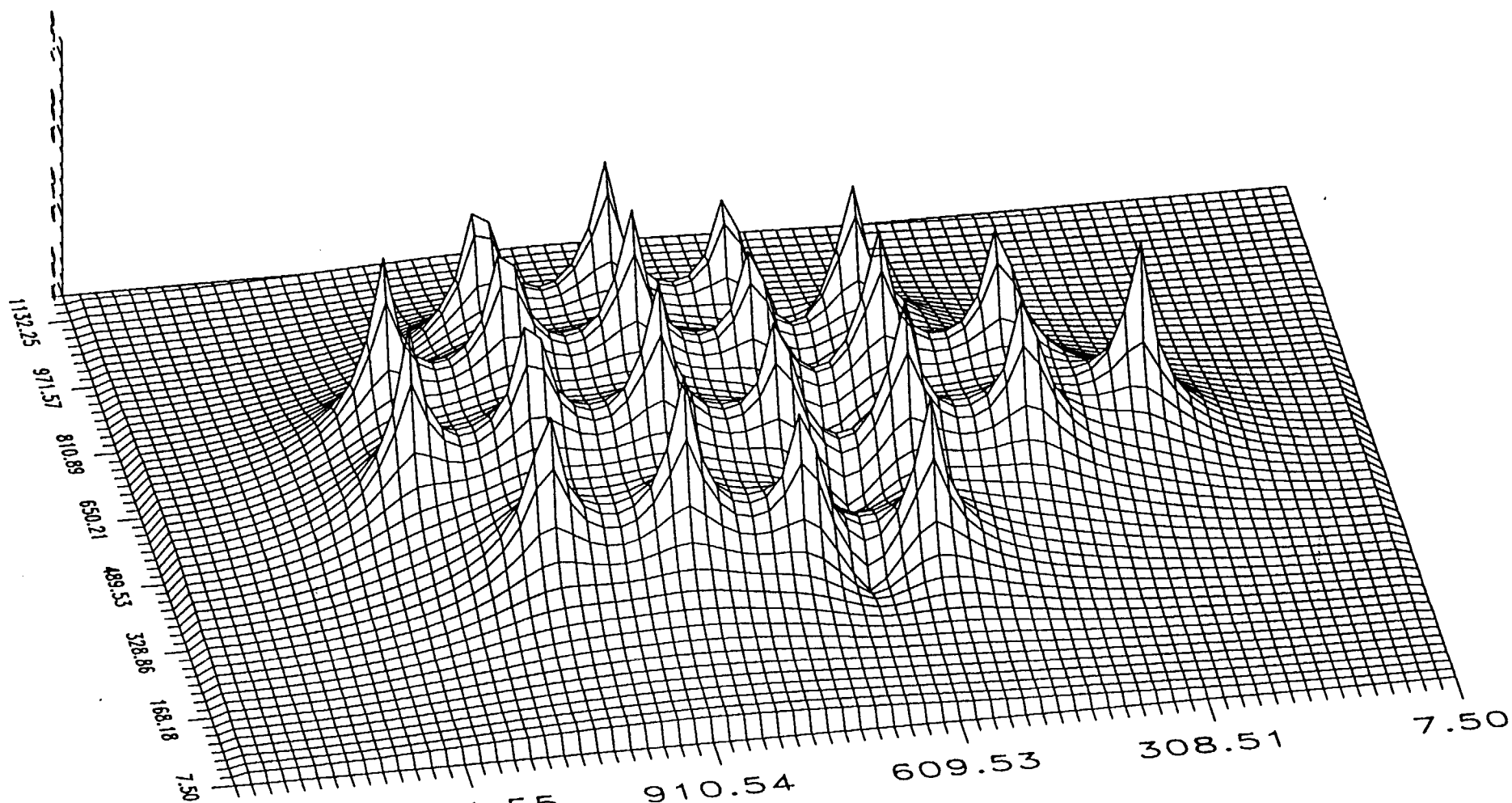




VES Pressure Dist. w/Air Sparging in Wells AS-1,2,3&4

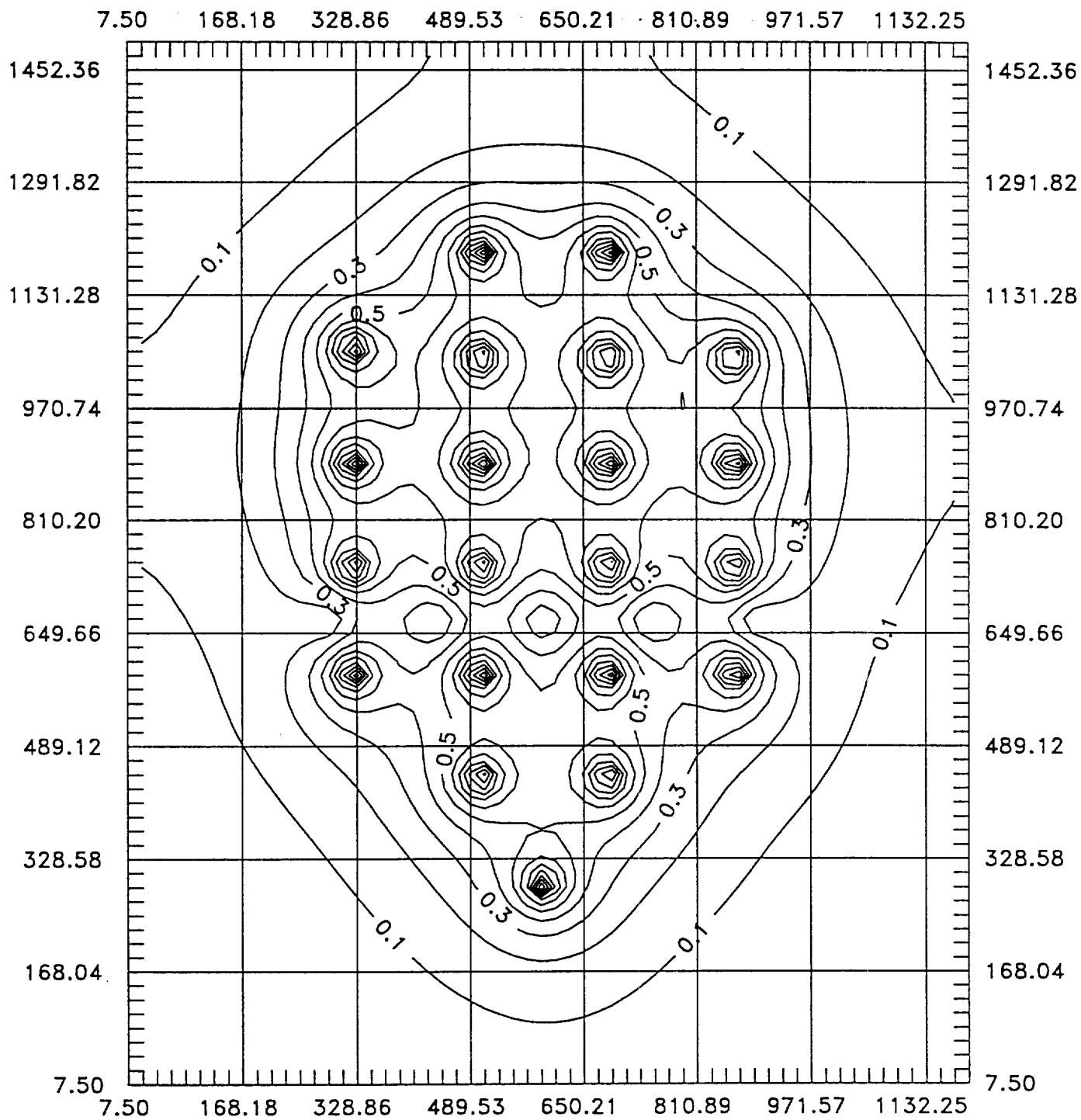
VES Pressure Dist. w/Air Sparging in Wells AS-1,2,3&4

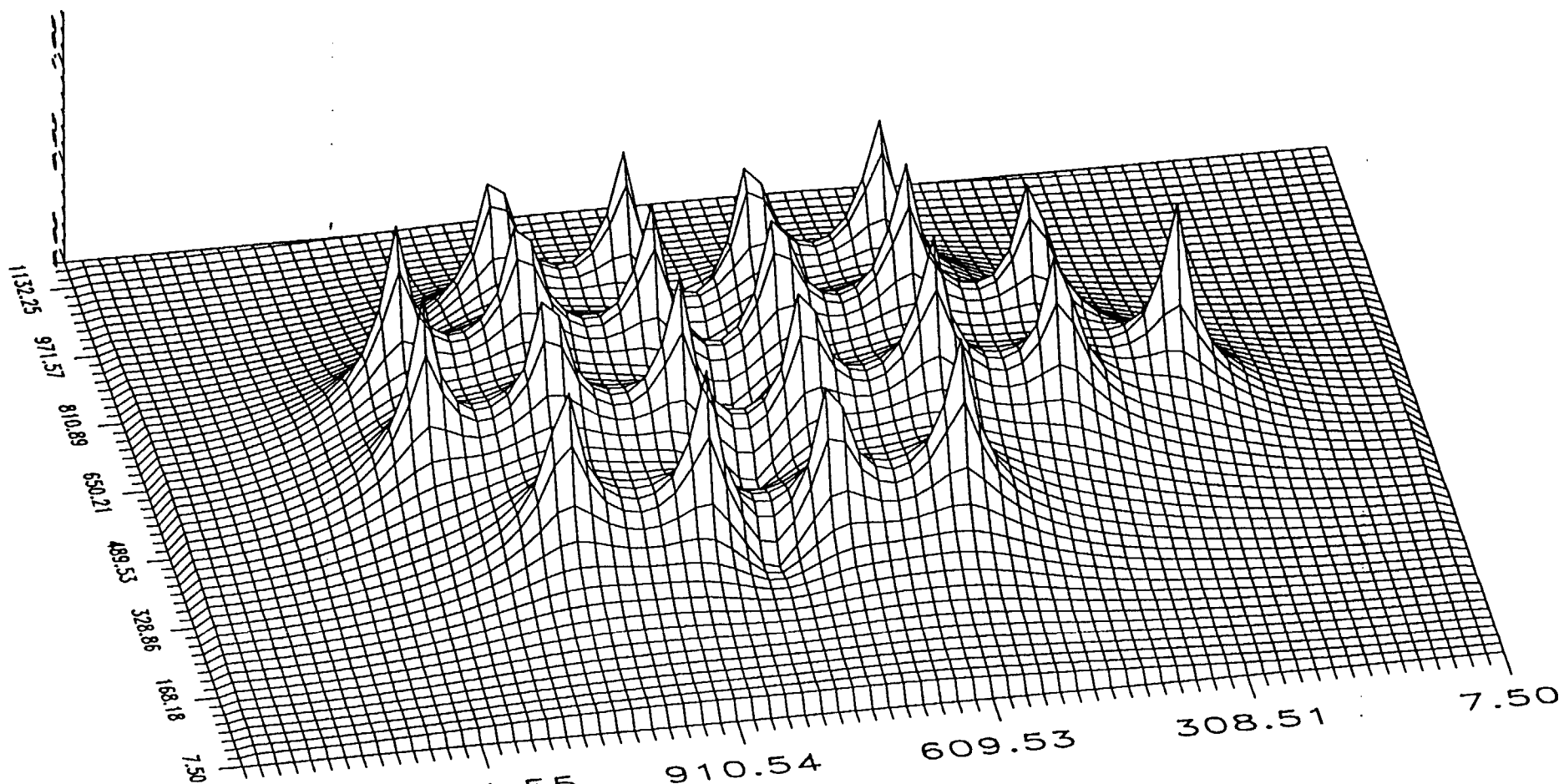




VES Pressure Dist. w/Air Sparging in Wells AS-5,6,7,8&9

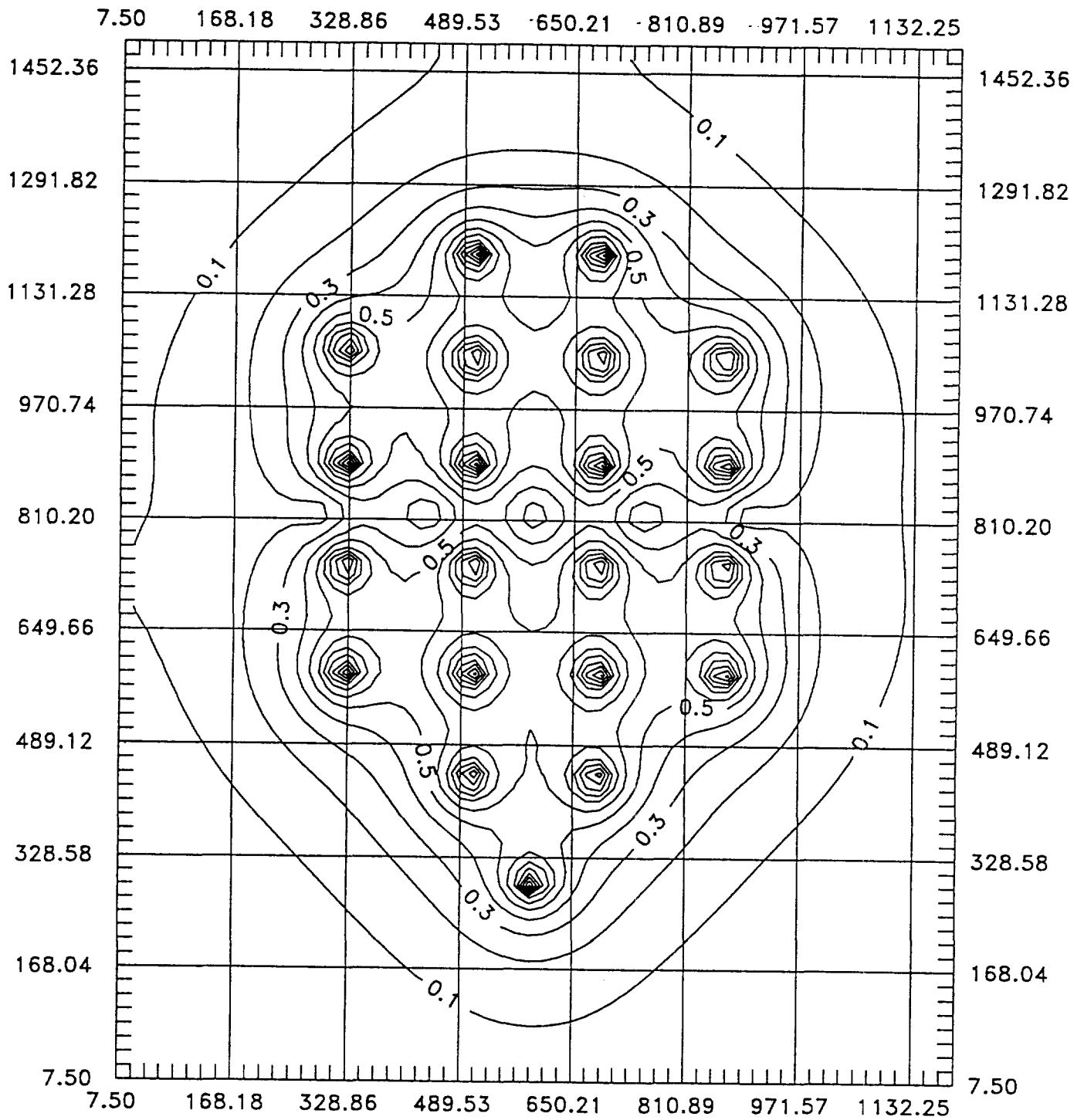
VES Pressure Dist. w/Air Sparging in Wells AS-5,6,7,8&9

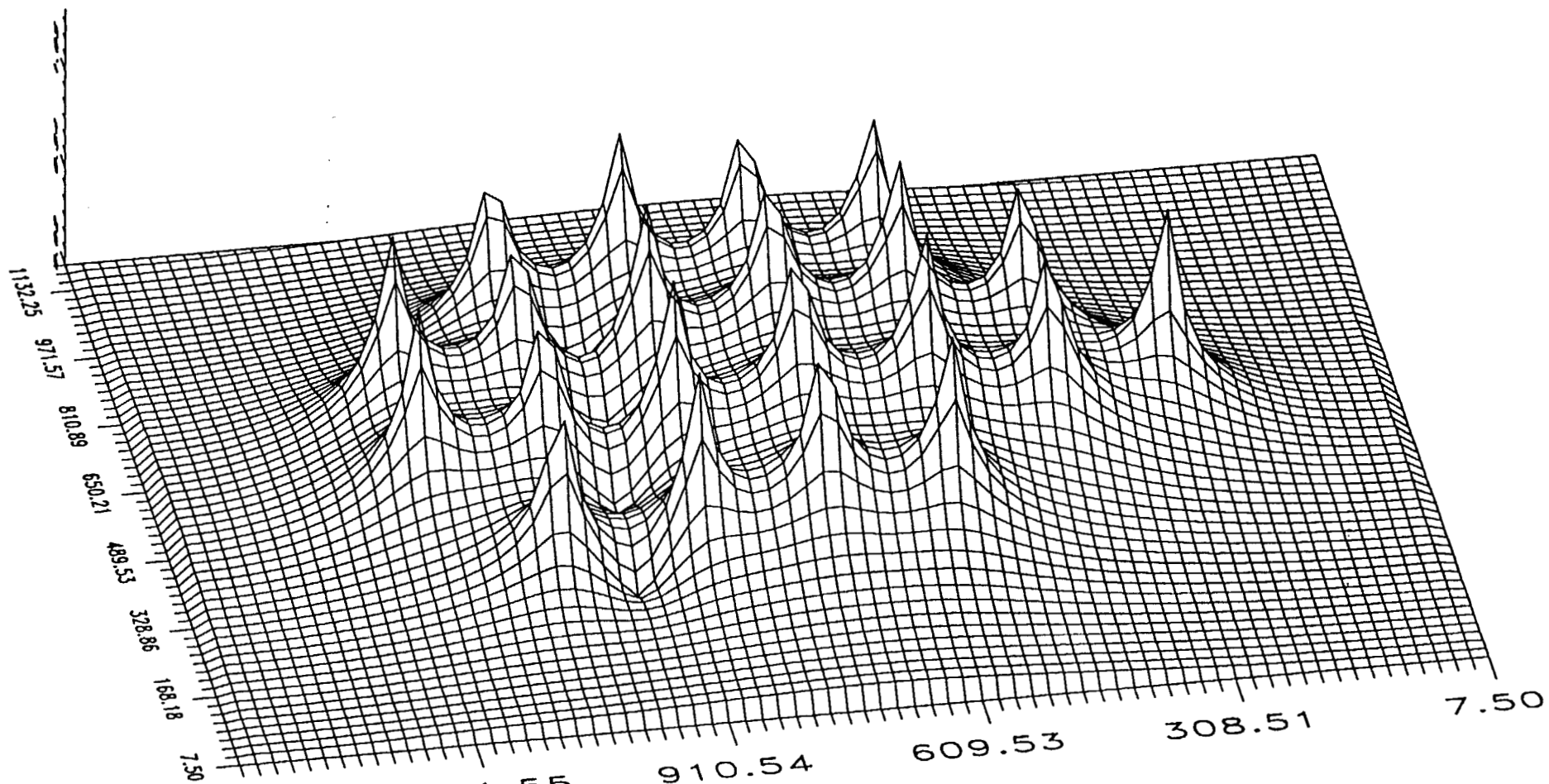




VES Pressure Dist. w/Air Sparging in Wells AS-10,11,12,13&14

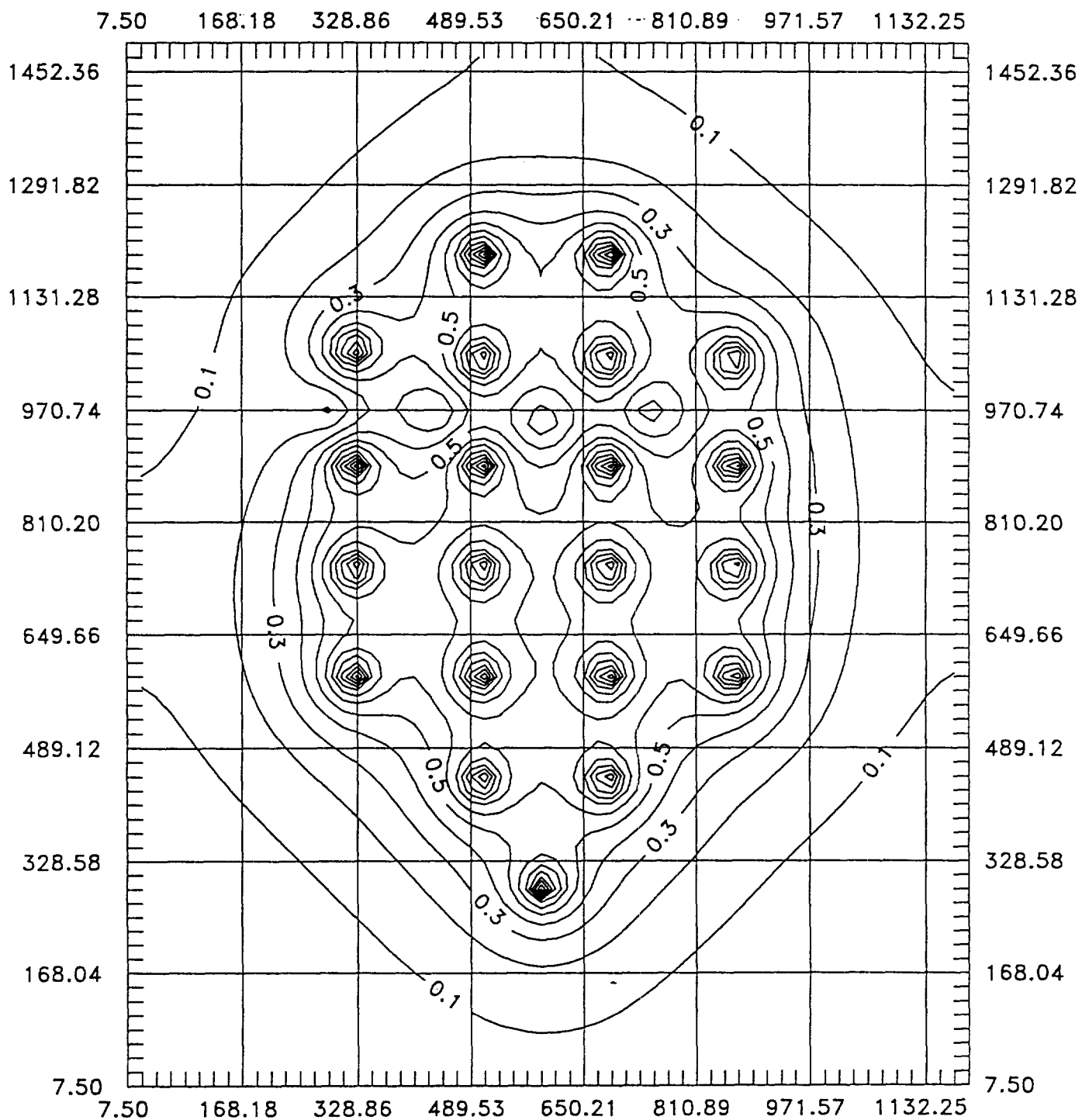
-S Pressure Dist. w/Air Sparging in Wells AS-10,11,12,13&14

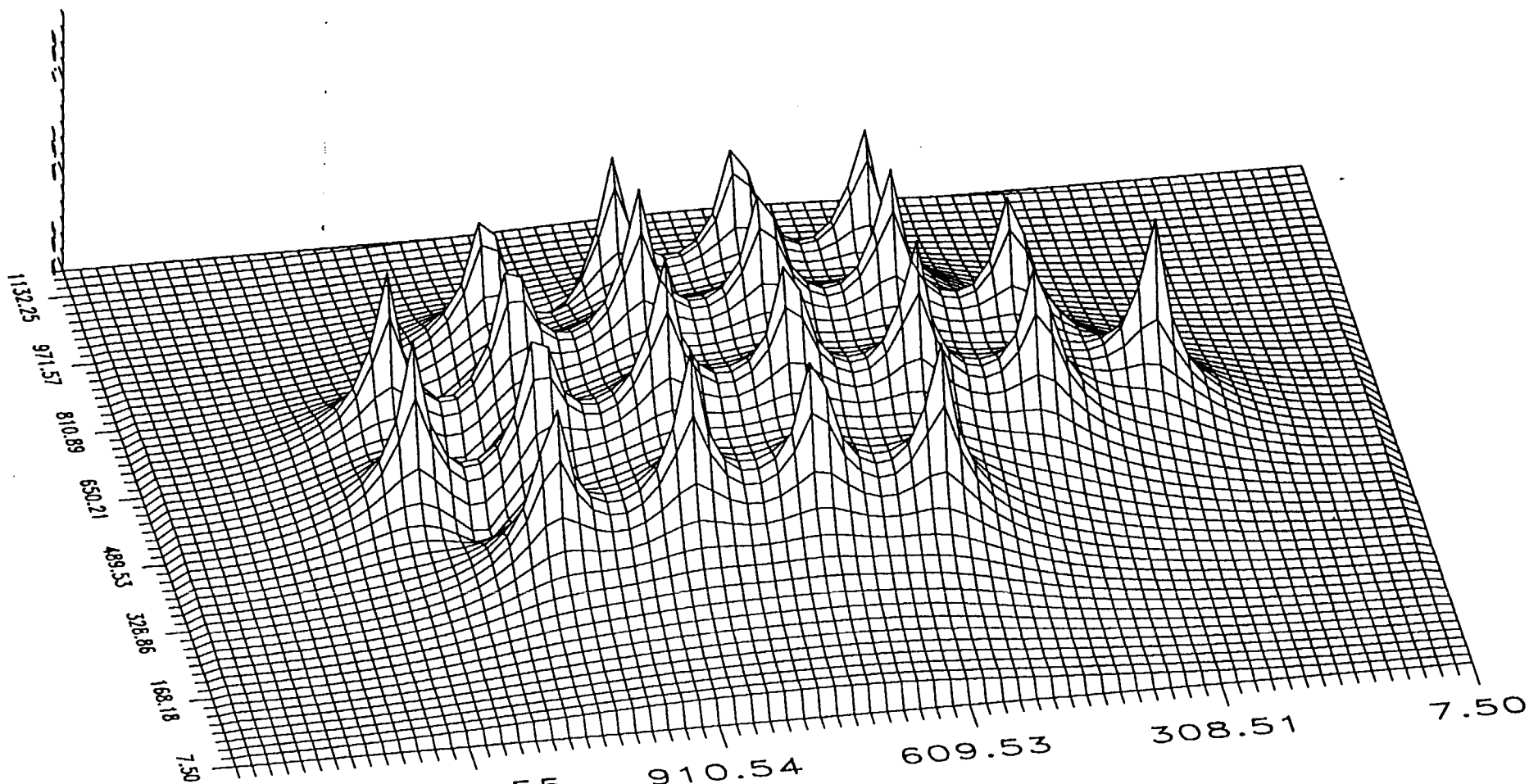




VES Pressure Dist. w/Air Sparging in Wells AS-15,16,17&18

VES Pressure Dist. w/Air Sparging in Wells AS-15,16,17,&18





VES Pressure Dist. w/Air Sparging in Wells AS-19,20,21&22

SECTION 7

Estimate of Remediation Time

ESTIMATE OF REMEDIATION TIME FOR THE SOIL VENTING / AIR SPARGING SYSTEM

Estimate Approach

The approach used to estimate the remediation time required for the FS-12 site will include the following steps:

- The program "Venting" will be used to estimate the remediation time for the site for the vapor extraction system alone.
- The remediation time for the groundwater will be calculated using the method presented in the paper "Air Sparging Model for Predicting Groundwater Cleanup Rate" by Katharine Sellars and Robert P. Schreiber.
- The effect of the mass removal by the air sparging will be added to the "Venting" results.

Input Required for the VENTING Program

- Air Flow Rate - 21 wells @ 150 SCFM each for a total flow of 3,150 SCFM.
- Spill Quantity - 70,000 Gallons
- Venting Period - 1000 days
- Spill Composition File - GASOLD.CMP This is one of the options in the VENTING program and this file uses the components of "OLD GASOLINE" which will be similar to the old JP-4 at the FS-12 MMR site. Samples were taken of the jet fuel from wells at the FS-12 site, but individual components were not identified by laboratory analysis. However boiling point analysis was performed on the Jet fuel sample and the results indicated that the jet fuel had a range of boiling points from 87° C to 244° C. The "Old Gas" file has a range of boiling points from 28° C to 226° C. Only 13.8% of the mass of the "Old Gas" file has a boiling point lower than the actual boiling point of the Jet fuel sample. The Old gas file will give appropriate results for this estimate.
- Step Time - Minimum 1 day and a Maximum 25 day step time will be used.
- Organic Carbon Content of .001 will be used. The outwash sand contains very little organic matter.
- Porosity of the outwash sand is approximately 35% and a Water content of 15% will be used and an air filled porosity of 20% will be used.

- Venting Efficiency Factor

$$\frac{\text{Airflow Passing through Contaminated Soil}}{\text{Total Air Flow}}$$

Since in this case the well will be screened only in the contaminated zone, a efficiency factor of 25% will be used. This small of factor will give a conservative estimate of the remediation time and will account for the losses in efficiency as the site becomes cleaner.

•Biodecay Efficiency Factor - The normal range of biodecay due to soil vapor extraction is from 25 to 40 %. A conservative value of 30% will be used for this site for the remediation time estimates. This site has a very high bio potential based on the sample analysis by Microbial Insights and the fact that the air sparging will provide a source of oxygen to the existing microbes.

The Data in this section includes:

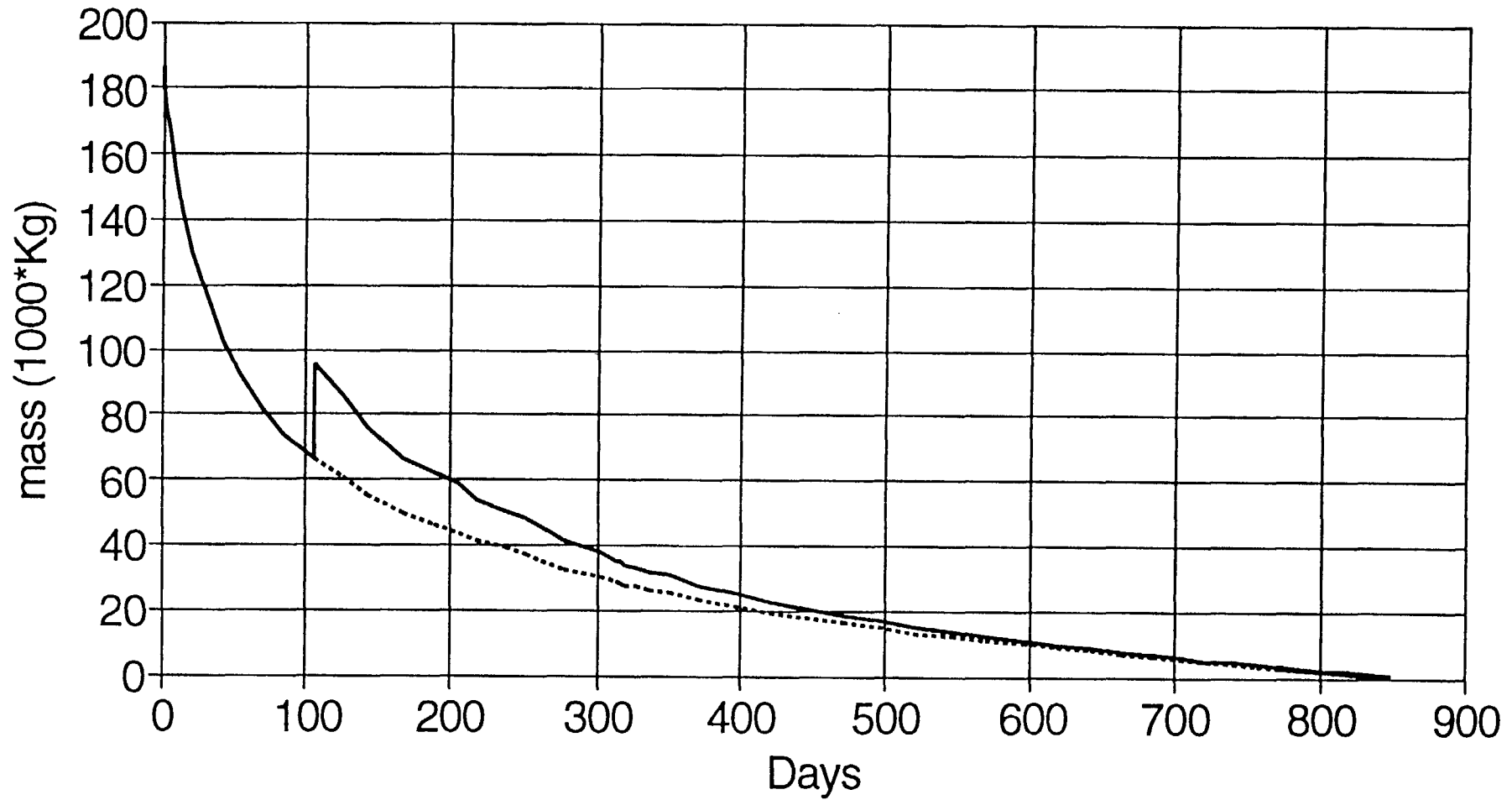
- Plot of total Mass Removal vs. Time
- Spreadsheet file of input data for plot.
- Printout of the VENTING output file from the VENTING analysis.
- Copy of the paper "Air Sparging Model for Predicting Groundwater Cleanup Rate"
- Calculation of Air Sparging model cleanup rates.

Results

The attached plot shows the remedial time should take about two years. This is made using some fairly conservative assumptions therefore the cleanup time could be some what shorter. The Air Sparging system was assumed to begin operation about 100 days after the start of the Soil vapor extraction system.

MMR Soil Venting

Total Mass Removal



— W/ Air Sparging W/O Air Sparging

VENTING Removal Rate Of Hydrocarbons

Time Days	Mass Remainin Soil venting	Mass Remaining SVE and AS
0.00	186.22	186.22
0.00	186.22	186.22
1.00	180.99	180.99
2.50	174.18	174.18
4.75	165.68	165.68
8.13	155.41	155.41
13.19	143.38	143.38
20.78	129.54	129.54
32.17	114.05	114.05
43.02	102.33	102.33
53.35	92.98	92.98
68.85	82.47	82.47
83.61	74.42	74.42
105.70	65.70	65.70
105.75	65.82	95.50
126.83	60.89	86.38
142.65	55.41	78.16
166.37	49.40	68.57
188.96	46.29	62.58
205.90	43.98	58.40
218.61	41.33	54.49
237.67	39.39	50.86
251.97	37.49	47.83
262.69	35.24	44.81
278.77	32.41	40.94
302.90	30.12	37.29
313.75	28.79	35.42
316.47	28.36	34.86
320.54	27.89	34.20
326.64	27.25	33.29
335.80	26.34	31.99
349.54	25.08	30.20
370.15	23.38	27.79
395.15	21.41	25.09
420.15	19.50	22.57
445.15	17.79	20.36
470.15	16.19	18.34
495.15	14.73	16.52

520.15	13.43	14.93
545.15	12.16	13.41
570.15	10.96	12.00
595.15	9.86	10.73
618.96	8.79	9.52
641.64	7.81	8.43
663.23	6.91	7.44
683.80	6.07	6.53
703.39	5.30	5.70
722.04	4.65	5.00
739.81	3.98	4.28
756.73	3.34	3.61
772.85	2.75	2.99
788.19	2.19	2.40
803.54	1.67	1.86
818.89	1.40	1.58
833.51	0.88	1.03
848.12	0.38	0.52

File:VENTEFF.WQ1

TITLE: MMR-25%

SPECIES	MOL. WEIGHT	- - VAP PRESSURE	- - BOILING- TEMP	- -SOLUB ILITY	- - KOC -
	gm/mole	atm	deg. c	mg/L	g/g
isopentane	.7220E+02	.7800E+00	.2800E+02	.4800E+02	.1862E+04
n-pentane	.7220E+02	.5700E+00	.3600E+02	.4000E+02	.2511E+04
2,3-dimethylbutane	.8620E+02	.2600E+00	.5700E+02	.2000E+02	.4786E+04
n-hexane	.8620E+02	.1600E+00	.6870E+02	.1300E+02	.8710E+04
benzene	.7810E+02	.1000E+00	.8010E+02	.1780E+04	.1350E+03
2,3-dimethylpentane	.1002E+03	.7200E-01	.8980E+02	.5300E+01	.1660E+05
n-heptane	.1002E+03	.4600E-01	.9800E+02	.3000E+01	.3000E+05
toluene	.9210E+02	.2900E-01	.1110E+03	.5150E+03	.4900E+03
2-methylheptane	.1142E+03	.2100E-01	.1160E+03	.9000E+00	.7763E+05
n-octane	.1142E+03	.1400E-01	.1260E+03	.7000E+00	.1047E+06
p-xylene	.1062E+03	.8600E-02	.1384E+03	.1980E+03	.1413E+04
3,3,4-trimethylhexane	.1283E+03	.7300E-02	.1400E+03	.1400E+01	.1479E+06
3,3,5-trimethylheptane	.1423E+03	.3700E-02	.1560E+03	.8000E+00	.3890E+06
n-propylbenzene	.1202E+03	.3300E-02	.1590E+03	.6000E+02	.4786E+04
1,3,5-trimethylbenzene	.1202E+03	.2400E-02	.1650E+03	.7300E+02	.1288E+05
1,2,4-trimethylbenzene	.1202E+03	.1900E-02	.1690E+03	.5700E+02	.1288E+05
methylpropylbenzene	.1342E+03	.1000E-02	.1820E+03	.6800E+01	.3388E+05
dimethylethylbenzene	.1342E+03	.7000E-03	.1900E+03	.2100E+02	.4467E+05
1,2,4,5-tetramethylbenzene	.1342E+03	.4600E-03	.1960E+03	.3500E+01	.1288E+05
n-dodecane	.1703E+03	.4000E-03	.2160E+03	.4000E-02	.1537E+04
naphthalene	.1282E+03	.1400E-03	.2180E+03	.3300E+02	.1738E+04
n-hexylbenzene	.1623E+03	.1000E-03	.2260E+03	.1300E+01	.3090E+06

page 1

2-methylheptane	.9311E+07	.0000E+00	.0000E+00	.3818E+02
n-octane	.9311E+07	.0000E+00	.0000E+00	.3818E+02
p-xylene	.2309E+08	.0000E+00	.0000E+00	.9468E+02
3,3,4-trimethylhexane	.4656E+07	.0000E+00	.0000E+00	.1909E+02
3,3,5-trimethylheptane	.4656E+07	.0000E+00	.0000E+00	.1909E+02
n-propylbenzene	.1546E+08	.0000E+00	.0000E+00	.6338E+02
1,3,5-trimethylbenzene	.4656E+07	.0000E+00	.0000E+00	.1909E+02
1,2,4-trimethylbenzene	.4656E+07	.0000E+00	.0000E+00	.1909E+02
methylpropylbenzene	.6890E+07	.0000E+00	.0000E+00	.2825E+02
dimethylethylbenzene	.7449E+07	.0000E+00	.0000E+00	.3054E+02
1,2,4,5-tetramethylbenze	.7449E+07	.0000E+00	.0000E+00	.3054E+02
n-dodecane	.5400E+07	.0000E+00	.0000E+00	.2214E+02
napthalene	.1862E+07	.0000E+00	.0000E+00	.7636E+01
n-hexylbenzene	.2235E+07	.0000E+00	.0000E+00	.9163E+01

TIME	=	.0000	[days]
TOTAL MASS OF HYDROCARBON	=	.18622E+06	[kg]
TOTAL MASS IN VAPOR PHASE	=	.49101E+04	[kg]
TOTAL MASS IN OIL PHASE	=	.14896E+06	[kg]
TOTAL MASS IN WATER PHASE	=	.23289E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.30334E+05	[kg]
HYDROCARBON MASS PER SOIL MASS	=	.76358E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.3724E+07	.4925E-04	.1970E-03	.1527E+02
n-pentane	.2048E+07	.2043E-04	.8173E-04	.8399E+01
2,3-dimethylbutane	.1117E+08	.5755E-04	.2302E-03	.4581E+02
n-hexane	.6890E+07	.2252E-04	.9007E-04	.2825E+02
benzene	.1862E+07	.2834E-05	.1133E-04	.7636E+01
2,3-dimethylpentane	.1899E+08	.2908E-04	.1163E-03	.7789E+02
n-heptane	.1490E+08	.1163E-04	.4653E-04	.6109E+02
toluene	.1955E+08	.1069E-04	.4277E-04	.8018E+02
2-methylheptane	.9311E+07	.3315E-05	.1326E-04	.3818E+02
n-octane	.9311E+07	.3315E-05	.1326E-04	.3818E+02
p-xylene	.2309E+08	.6165E-05	.2466E-04	.9468E+02
3,3,4-trimethylhexane	.4656E+07	.0000E+00	.0000E+00	.1909E+02
3,3,5-trimethylheptane	.4656E+07	.0000E+00	.0000E+00	.1909E+02
n-propylbenzene	.1546E+08	.0000E+00	.0000E+00	.6338E+02
1,3,5-trimethylbenzene	.4656E+07	.0000E+00	.0000E+00	.1909E+02
1,2,4-trimethylbenzene	.4656E+07	.0000E+00	.0000E+00	.1909E+02
methylpropylbenzene	.6890E+07	.0000E+00	.0000E+00	.2825E+02
dimethylethylbenzene	.7449E+07	.0000E+00	.0000E+00	.3054E+02
1,2,4,5-tetramethylbenze	.7449E+07	.0000E+00	.0000E+00	.3054E+02
n-dodecane	.5400E+07	.0000E+00	.0000E+00	.2214E+02
napthalene	.1862E+07	.0000E+00	.0000E+00	.7636E+01
n-hexylbenzene	.2235E+07	.0000E+00	.0000E+00	.9163E+01

SPECIES	GAS	SPECIES MASS [g] IN OIL	WATER	SOLID
isopentane	.1461E+07	.2278E+07	.3019E+05	.4067E+06
n-pentane	.5567E+06	.1365E+07	.1384E+05	.2514E+06
2,3-dimethylbutane	.1330E+07	.8767E+07	.3161E+05	.1095E+07
n-hexane	.4897E+06	.5576E+07	.1267E+05	.7984E+06
benzene	.8079E+05	.1074E+07	.5175E+06	.5055E+06
2,3-dimethylpentane	.5902E+06	.1672E+08	.1225E+05	.1471E+07
n-heptane	.2858E+06	.1326E+08	.5439E+04	.1180E+07
toluene	.2340E+06	.1395E+08	.1333E+07	.4726E+07
2-methylheptane	.7869E+05	.8637E+07	.8948E+03	.5025E+06
n-octane	.5170E+05	.8640E+07	.6960E+03	.5271E+06
p-xylene	.7749E+05	.1746E+08	.5250E+06	.5366E+07
3,3,4-trimethylhexane	.1307E+05	.3941E+07	.6195E+03	.6629E+06
3,3,5-trimethylheptane	.6457E+04	.3746E+07	.3192E+03	.8982E+06
n-propylbenzene	.1906E+05	.1215E+08	.9408E+05	.3257E+07
1,3,5-trimethylbenzene	.4106E+04	.2516E+07	.3448E+05	.3213E+07
1,2,4-trimethylbenzene	.3209E+04	.2774E+07	.2692E+05	.2509E+07
methylpropylbenzene	.2429E+04	.5789E+07	.4257E+04	.1044E+07
dimethylethylbenzene	.1813E+04	.4222E+07	.1421E+05	.4593E+07
1,2,4,5-tetramethylbenze	.1163E+04	.7179E+07	.2369E+04	.2208E+06
n-dodecane	.7583E+03	.5399E+07	.1547E+01	.1720E+02
napthalene	.8382E+02	.1768E+07	.5845E+04	.7350E+05
n-hexylbenzene	.7108E+02	.1756E+07	.2183E+03	.4879E+06

 end of initial conditions

TIME	=	2.0000	[days]
TOTAL MASS OF HYDROCARBON	=	.17664E+06	[kg]
TOTAL MASS IN VAPOR PHASE	=	.40701E+04	[kg]
TOTAL MASS IN OIL PHASE	=	.13991E+06	[kg]
TOTAL MASS IN WATER PHASE	=	.23804E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.31236E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.51430E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.51431E+01	[%]
HYDROCARBON MASS PER SOIL MASS	=	.72431E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.2131E+07	.3947E+01	.1579E+02	.8738E+01
n-pentane	.1307E+07	.1837E+01	.7346E+01	.5359E+01
2,3-dimethylbutane	.8625E+07	.6313E+01	.2525E+02	.3536E+02
n-hexane	.5827E+07	.2633E+01	.1053E+02	.2389E+02
benzene	.1728E+07	.3319E+00	.1327E+01	.7086E+01
2,3-dimethylpentane	.1747E+08	.3776E+01	.1510E+02	.7163E+02
n-heptane	.1413E+08	.1908E+01	.7634E+01	.5793E+02
toluene	.1904E+08	.1267E+01	.5067E+01	.7808E+02
2-methylheptane	.9083E+07	.5651E+00	.2260E+01	.3724E+02
n-octane	.9160E+07	.3745E+00	.1498E+01	.3756E+02
p-xylene	.2291E+08	.4545E+00	.1818E+01	.9393E+02
3,3,4-trimethylhexane	.4621E+07	.8655E-01	.3462E+00	.1895E+02
3,3,5-trimethylheptane	.4639E+07	.4066E-01	.1626E+00	.1902E+02
n-propylbenzene	.1541E+08	.1171E+00	.4683E+00	.6318E+02
1,3,5-trimethylbenzene	.4649E+07	.1681E-01	.6725E-01	.1906E+02
1,2,4-trimethylbenzene	.4650E+07	.1471E-01	.5884E-01	.1907E+02
methylpropylbenzene	.6884E+07	.1606E-01	.6423E-01	.2823E+02
dimethylethylbenzene	.7446E+07	.7869E-02	.3147E-01	.3053E+02
1,2,4,5-tetramethylbenze	.7445E+07	.8918E-02	.3567E-01	.3053E+02
n-dodecane	.5398E+07	.6052E-02	.2421E-01	.2213E+02
napthalene	.1862E+07	.6326E-03	.2530E-02	.7635E+01
n-hexylbenzene	.2234E+07	.4377E-03	.1751E-02	.9162E+01

TIME	=	5.0000	[days]
TOTAL MASS OF HYDROCARBON	=	.16528E+06	[kg]
TOTAL MASS IN VAPOR PHASE	=	.32092E+04	[kg]
TOTAL MASS IN OIL PHASE	=	.12877E+06	[kg]
TOTAL MASS IN WATER PHASE	=	.24154E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.32174E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.61006E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.11244E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.67773E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.9745E+06	.1909E+01	.7636E+01	.3996E+01
n-pentane	.6859E+06	.1025E+01	.4101E+01	.2812E+01
2,3-dimethylbutane	.5838E+07	.4600E+01	.1840E+02	.2394E+02
n-hexane	.4498E+07	.2194E+01	.8775E+01	.1844E+02
benzene	.1530E+07	.3096E+00	.1238E+01	.6272E+01
2,3-dimethylpentane	.1529E+08	.3594E+01	.1438E+02	.6271E+02
n-heptane	.1297E+08	.1908E+01	.7631E+01	.5319E+02
toluene	.1822E+08	.1296E+01	.5182E+01	.7472E+02
2-methylheptane	.8724E+07	.5932E+00	.2373E+01	.3577E+02
n-octane	.8918E+07	.3986E+00	.1594E+01	.3657E+02
p-xylene	.2260E+08	.4814E+00	.1926E+01	.9268E+02
3,3,4-trimethylhexane	.4564E+07	.9265E-01	.3706E+00	.1872E+02
3,3,5-trimethylheptane	.4613E+07	.4362E-01	.1745E+00	.1891E+02
n-propylbenzene	.1533E+08	.1254E+00	.5017E+00	.6286E+02
1,3,5-trimethylbenzene	.4637E+07	.1761E-01	.7043E-01	.1902E+02
1,2,4-trimethylbenzene	.4640E+07	.1550E-01	.6201E-01	.1902E+02
methylpropylbenzene	.6873E+07	.1736E-01	.6945E-01	.2818E+02
dimethylethylbenzene	.7440E+07	.8279E-02	.3312E-01	.3051E+02
1,2,4,5-tetramethylbenze	.7439E+07	.9778E-02	.3911E-01	.3050E+02

n-dodecane	.5394E+07	.6663E-02	.2665E-01	.2212E+02
napthalene	.1861E+07	.6930E-03	.2772E-02	.7632E+01
n-hexylbenzene	.2234E+07	.4714E-03	.1885E-02	.9161E+01

TIME	=	9.5000	[days]
TOTAL MASS OF HYDROCARBON	=	.15249E+06	[kg]
TOTAL MASS IN VAPOR PHASE	=	.26193E+04	[kg]
TOTAL MASS IN OIL PHASE	=	.11883E+06	[kg]
TOTAL MASS IN WATER PHASE	=	.25174E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.34332E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.68680E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.18112E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.62529E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.3385E+06	.6997E+00	.2799E+01	.1388E+01
n-pentane	.2809E+06	.4456E+00	.1782E+01	.1152E+01
2,3-dimethylbutane	.3299E+07	.2794E+01	.1118E+02	.1353E+02
n-hexane	.3044E+07	.1600E+01	.6400E+01	.1248E+02
benzene	.1269E+07	.2701E+00	.1080E+01	.5204E+01
2,3-dimethylpentane	.1241E+08	.3169E+01	.1268E+02	.5090E+02
n-heptane	.1133E+08	.1811E+01	.7246E+01	.4644E+02
toluene	.1700E+08	.1289E+01	.5155E+01	.6969E+02
2-methylheptane	.8172E+07	.6070E+00	.2428E+01	.3351E+02
n-octane	.8540E+07	.4169E+00	.1668E+01	.3502E+02
p-xylene	.2212E+08	.5047E+00	.2019E+01	.9070E+02
3,3,4-trimethylhexane	.4475E+07	.9829E-01	.3931E+00	.1835E+02
3,3,5-trimethylheptane	.4570E+07	.4655E-01	.1862E+00	.1874E+02
n-propylbenzene	.1521E+08	.1337E+00	.5348E+00	.6235E+02
1,3,5-trimethylbenzene	.4620E+07	.1837E-01	.7348E-01	.1894E+02
1,2,4-trimethylbenzene	.4624E+07	.1628E-01	.6511E-01	.1896E+02
methylpropylbenzene	.6856E+07	.1873E-01	.7491E-01	.2811E+02
dimethylethylbenzene	.7432E+07	.8686E-02	.3475E-01	.3047E+02
1,2,4,5-tetramethylbenze	.7429E+07	.1071E-01	.4285E-01	.3046E+02
n-dodecane	.5387E+07	.7331E-02	.2933E-01	.2209E+02
napthalene	.1860E+07	.7586E-03	.3034E-02	.7628E+01
n-hexylbenzene	.2234E+07	.5065E-03	.2026E-02	.9159E+01

TIME	=	16.2500	[days]
TOTAL MASS OF HYDROCARBON	=	.13832E+06	[kg]
TOTAL MASS IN VAPOR PHASE	=	.19001E+04	[kg]
TOTAL MASS IN OIL PHASE	=	.10566E+06	[kg]
TOTAL MASS IN WATER PHASE	=	.25215E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.35941E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.76136E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.25725E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.56715E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.8416E+05	.1865E+00	.7460E+00	.3451E+00
n-pentane	.8419E+05	.1443E+00	.5770E+00	.3452E+00
2,3-dimethylbutane	.1454E+07	.1354E+01	.5415E+01	.5960E+01
n-hexane	.1700E+07	.9863E+00	.3945E+01	.6971E+01
benzene	.9537E+06	.2165E+00	.8658E+00	.3911E+01
2,3-dimethylpentane	.8940E+07	.2549E+01	.1020E+02	.3666E+02
n-heptane	.9106E+07	.1629E+01	.6517E+01	.3734E+02
toluene	.1521E+08	.1254E+01	.5016E+01	.6235E+02
2-methylheptane	.7336E+07	.6135E+00	.2454E+01	.3008E+02
n-octane	.7945E+07	.4367E+00	.1747E+01	.3258E+02
p-xylene	.2136E+08	.5335E+00	.2134E+01	.8758E+02
3,3,4-trimethylhexane	.4331E+07	.1056E+00	.4226E+00	.1776E+02
3,3,5-trimethylheptane	.4501E+07	.5057E-01	.2023E+00	.1846E+02
n-propylbenzene	.1500E+08	.1451E+00	.5803E+00	.6151E+02
1,3,5-trimethylbenzene	.4592E+07	.1937E-01	.7748E-01	.1883E+02
1,2,4-trimethylbenzene	.4599E+07	.1731E-01	.6926E-01	.1886E+02
methylpropylbenzene	.6827E+07	.2069E-01	.8276E-01	.2800E+02
dimethylethylbenzene	.7419E+07	.9235E-02	.3694E-01	.3042E+02
1,2,4,5-tetramethylbenze	.7413E+07	.1211E-01	.4845E-01	.3040E+02
n-dodecane	.5376E+07	.8345E-02	.3338E-01	.2204E+02
napthalene	.1859E+07	.8566E-03	.3426E-02	.7622E+01

n-hexylbenzene .2233E+07 .5568E-03 .2227E-02 .9156E+01

TIME = 26.3750 [days]
TOTAL MASS OF HYDROCARBON = .12286E+06 [kg]
TOTAL MASS IN VAPOR PHASE = .13736E+04 [kg]
TOTAL MASS IN OIL PHASE = .91256E+05 [kg]
TOTAL MASS IN WATER PHASE = .24939E+04 [kg]
TOTAL MASS IN SOLID PHASE = .38334E+05 [kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP = .83017E+01 [%]
CUMULATIVE CHANGE IN HYDROCARBON = .34027E+02 [%]
HYDROCARBON MASS PER SOIL MASS = .50376E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.1419E+05	.5385E-01	.2154E+00	.5820E-01
n-pentane	.1736E+05	.5145E-01	.2058E+00	.7117E-01
2,3-dimethylbutane	.4625E+06	.7632E+00	.3053E+01	.1897E+01
n-hexane	.7259E+06	.7502E+00	.3001E+01	.2977E+01
benzene	.6185E+06	.2388E+00	.9554E+00	.2536E+01
2,3-dimethylpentane	.5353E+07	.2763E+01	.1105E+02	.2195E+02
n-heptane	.6405E+07	.2080E+01	.8322E+01	.2626E+02
toluene	.1271E+08	.1830E+01	.7318E+01	.5211E+02
2-methylheptane	.6119E+07	.9377E+00	.3751E+01	.2509E+02
n-octane	.7026E+07	.7077E+00	.2831E+01	.2881E+02
p-xylene	.2015E+08	.8863E+00	.3545E+01	.8262E+02
3,3,4-trimethylhexane	.4098E+07	.1796E+00	.7183E+00	.1680E+02
3,3,5-trimethylheptane	.4388E+07	.8772E-01	.3509E+00	.1799E+02
n-propylbenzene	.1466E+08	.2513E+00	.1005E+01	.6013E+02
1,3,5-trimethylbenzene	.4547E+07	.3241E-01	.1296E+00	.1865E+02
1,2,4-trimethylbenzene	.4559E+07	.2930E-01	.1172E+00	.1869E+02
methylpropylbenzene	.6779E+07	.3685E-01	.1474E+00	.2780E+02
dimethylethylbenzene	.7398E+07	.1564E-01	.6255E-01	.3033E+02
1,2,4,5-tetramethylbenzene	.7383E+07	.2231E-01	.8925E-01	.3027E+02
n-dodecane	.5356E+07	.1553E-01	.6212E-01	.2196E+02
naphthalene	.1856E+07	.1576E-02	.6304E-02	.7610E+01
n-hexylbenzene	.2232E+07	.9862E-03	.3945E-02	.9151E+01

TIME = 36.0179 [days]
TOTAL MASS OF HYDROCARBON = .11055E+06 [kg]
TOTAL MASS IN VAPOR PHASE = .10528E+04 [kg]
TOTAL MASS IN OIL PHASE = .70384E+05 [kg]
TOTAL MASS IN WATER PHASE = .22373E+04 [kg]
TOTAL MASS IN SOLID PHASE = .35251E+05 [kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP = .66097E+01 [%]
CUMULATIVE CHANGE IN HYDROCARBON = .40637E+02 [%]
HYDROCARBON MASS PER SOIL MASS = .45329E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.1146E-01	.4586E-01	.0000E+00
n-pentane	.0000E+00	.1402E-01	.5609E-01	.0000E+00
2,3-dimethylbutane	.1347E+06	.2650E+00	.1060E+01	.5524E+00
n-hexane	.2860E+06	.3557E+00	.1423E+01	.1173E+01
benzene	.3853E+06	.1660E+00	.6638E+00	.1580E+01
2,3-dimethylpentane	.2988E+07	.1912E+01	.7648E+01	.1225E+02
n-heptane	.4271E+07	.1727E+01	.6907E+01	.1751E+02
toluene	.1038E+08	.1737E+01	.6948E+01	.4256E+02
2-methylheptane	.4935E+07	.9581E+00	.3832E+01	.2024E+02
n-octane	.6069E+07	.7746E+00	.3098E+01	.2488E+02
p-xylene	.1884E+08	.9777E+00	.3911E+01	.7726E+02
3,3,4-trimethylhexane	.3844E+07	.2057E+00	.8229E+00	.1576E+02
3,3,5-trimethylheptane	.4261E+07	.1023E+00	.4093E+00	.1747E+02
n-propylbenzene	.1428E+08	.2920E+00	.1168E+01	.5857E+02
1,3,5-trimethylbenzene	.4499E+07	.3539E-01	.1416E+00	.1845E+02
1,2,4-trimethylbenzene	.4515E+07	.3255E-01	.1302E+00	.1851E+02
methylpropylbenzene	.6723E+07	.4452E-01	.1781E+00	.2757E+02
dimethylethylbenzene	.7374E+07	.1734E-01	.6935E-01	.3024E+02
1,2,4,5-tetramethylbenzene	.7347E+07	.2865E-01	.1146E+00	.3013E+02
n-dodecane	.5331E+07	.2034E-01	.8135E-01	.2186E+02
naphthalene	.1852E+07	.2014E-02	.8057E-02	.7594E+01
n-hexylbenzene	.2230E+07	.1175E-02	.4701E-02	.9145E+01

TIME	=	45.2015	[days]
TOTAL MASS OF HYDROCARBON	=	.10108E+06	[kg]
TOTAL MASS IN VAPOR PHASE	=	.85483E+03	[kg]
TOTAL MASS IN OIL PHASE	=	.60811E+05	[kg]
TOTAL MASS IN WATER PHASE	=	.20494E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.35331E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.50846E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.45721E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.41446E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.3793E+05	.5214E-01	.2086E+00	.1555E+00
n-hexane	.1091E+06	.9536E-01	.3814E+00	.4472E+00
benzene	.2386E+06	.6904E-01	.2762E+00	.9782E+00
2,3-dimethylpentane	.1615E+07	.7405E+00	.2962E+01	.6621E+01
n-heptane	.2775E+07	.8066E+00	.3226E+01	.1138E+02
toluene	.8415E+07	.9694E+00	.3878E+01	.3451E+02
2-methylheptane	.3911E+07	.5524E+00	.2210E+01	.1604E+02
n-octane	.5177E+07	.4808E+00	.1923E+01	.2123E+02
p-xylene	.1756E+08	.6329E+00	.2532E+01	.7201E+02
3,3,4-trimethylhexane	.3591E+07	.1364E+00	.5457E+00	.1472E+02
3,3,5-trimethylheptane	.4132E+07	.6969E-01	.2788E+00	.1694E+02
n-propylbenzene	.1389E+08	.1986E+00	.7943E+00	.5697E+02
1,3,5-trimethylbenzene	.4452E+07	.2339E-01	.9355E-01	.1825E+02
1,2,4-trimethylbenzene	.4471E+07	.2172E-01	.8689E-01	.1833E+02
methylpropylbenzene	.6664E+07	.3128E-01	.1251E+00	.2732E+02
dimethylethylbenzene	.7351E+07	.1159E-01	.4638E-01	.3014E+02
1,2,4,5-tetramethylbenze	.7308E+07	.2100E-01	.8400E-01	.2996E+02
n-dodecane	.5303E+07	.1512E-01	.6050E-01	.2174E+02
napthalene	.1847E+07	.1473E-02	.5892E-02	.7575E+01
n-hexylbenzene	.2229E+07	.8212E-03	.3285E-02	.9138E+01

TIME	=	58.9771	[days]
TOTAL MASS OF HYDROCARBON	=	.89722E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.69821E+03	[kg]
TOTAL MASS IN OIL PHASE	=	.44328E+05	[kg]
TOTAL MASS IN WATER PHASE	=	.20348E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.43896E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.60987E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.51820E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.36789E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.2146E-01	.8584E-01	.0000E+00
n-hexane	.2761E+05	.4609E-01	.1844E+00	.1132E+00
benzene	.1196E+06	.6024E-01	.2410E+00	.4905E+00
2,3-dimethylpentane	.6175E+06	.5646E+00	.2258E+01	.2532E+01
n-heptane	.1366E+07	.7975E+00	.3190E+01	.5602E+01
toluene	.6028E+07	.1267E+01	.5070E+01	.2472E+02
2-methylheptane	.2581E+07	.7533E+00	.3013E+01	.1058E+02
n-octane	.3866E+07	.7423E+00	.2969E+01	.1585E+02
p-xylene	.1561E+08	.1046E+01	.4182E+01	.6399E+02
3,3,4-trimethylhexane	.3175E+07	.2353E+00	.9414E+00	.1302E+02
3,3,5-trimethylheptane	.3910E+07	.1256E+00	.5024E+00	.1603E+02
n-propylbenzene	.1324E+08	.3569E+00	.1428E+01	.5428E+02
1,3,5-trimethylbenzene	.4377E+07	.3957E-01	.1583E+00	.1795E+02
1,2,4-trimethylbenzene	.4400E+07	.3743E-01	.1497E+00	.1804E+02
methylpropylbenzene	.6557E+07	.5981E-01	.2392E+00	.2689E+02
dimethylethylbenzene	.7314E+07	.2001E-01	.8006E-01	.2999E+02
1,2,4,5-tetramethylbenze	.7228E+07	.4433E-01	.1773E+00	.2964E+02
n-dodecane	.5244E+07	.3314E-01	.1326E+00	.2150E+02
napthalene	.1840E+07	.3089E-02	.1236E-01	.7544E+01
n-hexylbenzene	.2226E+07	.1547E-02	.6187E-02	.9127E+01

TIME	=	72.0966	[days]
TOTAL MASS OF HYDROCARBON	=	.81076E+05	[kg]

TOTAL MASS IN VAPOR PHASE	=	.53625E+03	[kg]
TOTAL MASS IN OIL PHASE	=	.36781E+05	[kg]
TOTAL MASS IN WATER PHASE	=	.17462E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.43189E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.46427E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.56463E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.33244E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.6697E+04	.7882E-02	.3153E-01	.2746E-01
benzene	.5736E+05	.1929E-01	.7715E-01	.2352E+00
2,3-dimethylpentane	.2239E+06	.1485E+00	.5939E+00	.9181E+00
n-heptane	.6422E+06	.2732E+00	.1093E+01	.2633E+01
toluene	.4218E+07	.6083E+00	.2433E+01	.1730E+02
2-methylheptane	.1638E+07	.3557E+00	.1423E+01	.6718E+01
n-octane	.2805E+07	.4006E+00	.1602E+01	.1150E+02
p-xylene	.1373E+08	.6380E+00	.2552E+01	.5631E+02
3,3,4-trimethylhexane	.2784E+07	.1475E+00	.5900E+00	.1142E+02
3,3,5-trimethylheptane	.3689E+07	.8342E-01	.3337E+00	.1513E+02
n-propylbenzene	.1257E+08	.2370E+00	.9482E+00	.5153E+02
1,3,5-trimethylbenzene	.4300E+07	.2581E-01	.1032E+00	.1763E+02
1,2,4-trimethylbenzene	.4327E+07	.2466E-01	.9863E-01	.1774E+02
methylpropylbenzene	.6444E+07	.4190E-01	.1676E+00	.2642E+02
dimethylethylbenzene	.7275E+07	.1327E-01	.5309E-01	.2983E+02
1,2,4,5-tetramethylbenze	.7138E+07	.3334E-01	.1333E+00	.2927E+02
n-dodecane	.5176E+07	.2565E-01	.1026E+00	.2122E+02
napthalene	.1829E+07	.2316E-02	.9262E-02	.7500E+01
n-hexylbenzene	.2223E+07	.1081E-02	.4323E-02	.9115E+01

TIME	=	91.7759	[days]
TOTAL MASS OF HYDROCARBON	=	.71582E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.43717E+03	[kg]
TOTAL MASS IN OIL PHASE	=	.28905E+05	[kg]
TOTAL MASS IN WATER PHASE	=	.16451E+04	[kg]
TOTAL MASS IN SOLID PHASE	=	.43307E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.50981E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.61561E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.29352E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.2651E-02	.1060E-01	.0000E+00
benzene	.2127E+05	.1188E-01	.4752E-01	.8723E-01
2,3-dimethylpentane	.5496E+05	.6693E-01	.2677E+00	.2253E+00
n-heptane	.2152E+06	.1692E+00	.6768E+00	.8823E+00
toluene	.2498E+07	.6171E+00	.2468E+01	.1024E+02
2-methylheptane	.8027E+06	.3312E+00	.1325E+01	.3292E+01
n-octane	.1665E+07	.4520E+00	.1808E+01	.6827E+01
p-xylene	.1125E+08	.9072E+00	.3629E+01	.4614E+02
3,3,4-trimethylhexane	.2244E+07	.2142E+00	.8567E+00	.9199E+01
3,3,5-trimethylheptane	.3351E+07	.1339E+00	.5357E+00	.1374E+02
n-propylbenzene	.1155E+08	.3822E+00	.1529E+01	.4737E+02
1,3,5-trimethylbenzene	.4187E+07	.4145E-01	.1658E+00	.1717E+02
1,2,4-trimethylbenzene	.4218E+07	.4006E-01	.1602E+00	.1729E+02
methylpropylbenzene	.6256E+07	.7308E-01	.2923E+00	.2565E+02
dimethylethylbenzene	.7216E+07	.2182E-01	.8730E-01	.2959E+02
1,2,4,5-tetramethylbenze	.6974E+07	.6409E-01	.2564E+00	.2860E+02
n-dodecane	.5046E+07	.5152E-01	.2061E+00	.2069E+02
napthalene	.1812E+07	.4447E-02	.1779E-01	.7429E+01
n-hexylbenzene	.2218E+07	.1891E-02	.7565E-02	.9094E+01

TIME	=	110.5181	[days]
TOTAL MASS OF HYDROCARBON	=	.66140E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.48522E+03	[kg]
TOTAL MASS IN OIL PHASE	=	.10174E+05	[kg]

TOTAL MASS IN WATER PHASE	= .17595E+04	[kg]
TOTAL MASS IN SOLID PHASE	= .53776E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	= .29223E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	= .64483E+02	[%]
HYDROCARBON MASS PER SOIL MASS	= .27120E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.9602E+04	.3875E-02	.1550E-01	.3937E-01
2,3-dimethylpentane	.1653E+05	.2027E-01	.8109E-01	.6777E-01
n-heptane	.8465E+05	.6890E-01	.2756E+00	.3471E+00
toluene	.1686E+07	.3284E+00	.1313E+01	.6915E+01
2-methylheptane	.4183E+06	.2031E+00	.8124E+00	.1715E+01
n-octane	.1037E+07	.3317E+00	.1327E+01	.4253E+01
p-xylene	.9719E+07	.6433E+00	.2573E+01	.3985E+02
3,3,4-trimethylhexane	.1919E+07	.1712E+00	.6848E+00	.7869E+01
3,3,5-trimethylheptane	.3143E+07	.1095E+00	.4381E+00	.1289E+02
n-propylbenzene	.1088E+08	.3060E+00	.1224E+01	.4462E+02
1,3,5-trimethylbenzene	.4115E+07	.2893E-01	.1157E+00	.1687E+02
1,2,4-trimethylbenzene	.4147E+07	.2875E-01	.1150E+00	.1701E+02
methylpropylbenzene	.6125E+07	.6607E-01	.2643E+00	.2512E+02
dimethylethylbenzene	.7178E+07	.1561E-01	.6246E-01	.2943E+02
1,2,4,5-tetramethylbenze	.6799E+07	.8919E-01	.3568E+00	.2788E+02
n-dodecane	.4857E+07	.1002E+00	.4007E+00	.1991E+02
napthalene	.1788E+07	.5736E-02	.2295E-01	.7331E+01
n-hexylbenzene	.2215E+07	.1605E-02	.6418E-02	.9081E+01

TIME	= 124.5747	[days]
TOTAL MASS OF HYDROCARBON	= .60137E+05	[kg]
TOTAL MASS IN VAPOR PHASE	= .35670E+03	[kg]
TOTAL MASS IN OIL PHASE	= .91082E+04	[kg]
TOTAL MASS IN WATER PHASE	= .14210E+04	[kg]
TOTAL MASS IN SOLID PHASE	= .49250E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	= .32238E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	= .67707E+02	[%]
HYDROCARBON MASS PER SOIL MASS	= .24659E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.2693E-02	.1077E-01	.0000E+00
2,3-dimethylpentane	.0000E+00	.5813E-02	.2325E-01	.0000E+00
n-heptane	.2495E+05	.2100E-01	.8402E-01	.1023E+00
toluene	.9913E+06	.1955E+00	.7820E+00	.4065E+01
2-methylheptane	.1712E+06	.8703E-01	.3481E+00	.7020E+00
n-octane	.5316E+06	.1780E+00	.7122E+00	.2180E+01
p-xylene	.7902E+07	.5312E+00	.2125E+01	.3240E+02
3,3,4-trimethylhexane	.1523E+07	.1393E+00	.5574E+00	.6246E+01
3,3,5-trimethylheptane	.2855E+07	.1015E+00	.4058E+00	.1171E+02
n-propylbenzene	.9969E+07	.2854E+00	.1142E+01	.4088E+02
1,3,5-trimethylbenzene	.4018E+07	.2843E-01	.1137E+00	.1648E+02
1,2,4-trimethylbenzene	.4051E+07	.2830E-01	.1132E+00	.1661E+02
methylpropylbenzene	.5932E+07	.6555E-01	.2622E+00	.2432E+02
dimethylethylbenzene	.7126E+07	.1561E-01	.6244E-01	.2922E+02
1,2,4,5-tetramethylbenze	.6528E+07	.9164E-01	.3666E+00	.2677E+02
n-dodecane	.4556E+07	.1061E+00	.4245E+00	.1868E+02
napthalene	.1748E+07	.5937E-02	.2375E-01	.7166E+01
n-hexylbenzene	.2210E+07	.1630E-02	.6520E-02	.9061E+01

TIME	= 145.6597	[days]
TOTAL MASS OF HYDROCARBON	= .53665E+05	[kg]
TOTAL MASS IN VAPOR PHASE	= .27270E+03	[kg]
TOTAL MASS IN OIL PHASE	= .78854E+04	[kg]
TOTAL MASS IN WATER PHASE	= .11107E+04	[kg]
TOTAL MASS IN SOLID PHASE	= .44498E+05	[kg]

CHANGE IN HYDROCARBON MASS FOR TIME STEP = .34754E+01 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .71182E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .22005E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.5276E+04	.7270E-02	.2908E-01	.2164E-01
toluene	.4938E+06	.1556E+00	.6224E+00	.2025E+01
2-methylheptane	.5215E+05	.4403E-01	.1761E+00	.2138E+00
n-octane	.2123E+06	.1181E+00	.4724E+00	.8705E+00
p-xylene	.5938E+07	.6397E+00	.2559E+01	.2435E+02
3,3,4-trimethylhexane	.1087E+07	.1612E+00	.6446E+00	.4458E+01
3,3,5-trimethylheptane	.2472E+07	.1415E+00	.5660E+00	.1014E+02
n-propylbenzene	.8788E+07	.4044E+00	.1618E+01	.3603E+02
1,3,5-trimethylbenzene	.3886E+07	.4360E-01	.1744E+00	.1593E+02
1,2,4-trimethylbenzene	.3919E+07	.4350E-01	.1740E+00	.1607E+02
methylpropylbenzene	.5652E+07	.1011E+00	.4043E+00	.2318E+02
dimethylethylbenzene	.7053E+07	.2452E-01	.9809E-01	.2892E+02
1,2,4,5-tetramethylbenzene	.6121E+07	.1467E+00	.5867E+00	.2510E+02
n-dodecane	.4083E+07	.1747E+00	.6988E+00	.1674E+02
napthalene	.1699E+07	.9722E-02	.3889E-01	.6967E+01
n-hexylbenzene	.2202E+07	.2611E-02	.1044E-01	.9031E+01

TIME = 165.7406 [days]
 TOTAL MASS OF HYDROCARBON = .48410E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .21000E+03 [kg]
 TOTAL MASS IN OIL PHASE = .69108E+04 [kg]
 TOTAL MASS IN WATER PHASE = .88059E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .40409E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .28217E+01 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .74004E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .19850E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.1565E-02	.6259E-02	.0000E+00
toluene	.2305E+06	.5615E-01	.2246E+00	.9450E+00
2-methylheptane	.1596E+05	.1074E-01	.4298E-01	.6545E-01
n-octane	.8512E+05	.3776E-01	.1511E+00	.3490E+00
p-xylene	.4367E+07	.3647E+00	.1459E+01	.1791E+02
3,3,4-trimethylhexane	.7818E+06	.9060E-01	.3624E+00	.3206E+01
3,3,5-trimethylheptane	.2150E+07	.9573E-01	.3829E+00	.8815E+01
n-propylbenzene	.7709E+07	.2756E+00	.1102E+01	.3161E+02
1,3,5-trimethylbenzene	.3750E+07	.3235E-01	.1294E+00	.1537E+02
1,2,4-trimethylbenzene	.3783E+07	.3234E-01	.1293E+00	.1551E+02
methylpropylbenzene	.5386E+07	.7525E-01	.3010E+00	.2209E+02
dimethylethylbenzene	.6976E+07	.1866E-01	.7466E-01	.2861E+02
1,2,4,5-tetramethylbenzene	.5724E+07	.1119E+00	.4476E+00	.2347E+02
n-dodecane	.3627E+07	.1355E+00	.5421E+00	.1487E+02
napthalene	.1629E+07	.7521E-02	.3008E-01	.6681E+01
n-hexylbenzene	.2195E+07	.2021E-02	.8085E-02	.9001E+01

TIME = 190.7406 [days]
 TOTAL MASS OF HYDROCARBON = .45264E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .18070E+03 [kg]
 TOTAL MASS IN OIL PHASE = .63127E+04 [kg]
 TOTAL MASS IN WATER PHASE = .75227E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .38024E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .16896E+01 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .75694E+02 [%]

HYDROCARBON MASS PER SOIL MASS = .18560E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.1245E+06	.2536E-01	.1014E+00	.5105E+00
2-methylheptane	.6507E+04	.3740E-02	.1496E-01	.2668E-01
n-octane	.4349E+05	.1647E-01	.6590E-01	.1783E+00
p-xylene	.3452E+07	.2413E+00	.9653E+00	.1415E+02
3,3,4-trimethylhexane	.6269E+06	.6118E-01	.2447E+00	.2571E+01
3,3,5-trimethylheptane	.1964E+07	.7341E-01	.2936E+00	.8053E+01
n-propylbenzene	.7016E+07	.2103E+00	.8412E+00	.2877E+02
1,3,5-trimethylbenzene	.3652E+07	.2624E-01	.1050E+00	.1497E+02
1,2,4-trimethylbenzene	.3686E+07	.2626E-01	.1050E+00	.1511E+02
methylpropylbenzene	.5217E+07	.6134E-01	.2454E+00	.2139E+02
dimethylethylbenzene	.6921E+07	.1543E-01	.6171E-01	.2838E+02
1,2,4,5-tetramethylbenze	.5465E+07	.9276E-01	.3710E+00	.2241E+02
n-dodecane	.3339E+07	.1142E+00	.4568E+00	.1369E+02
naphthalene	.1560E+07	.6200E-02	.2480E-01	.6397E+01
n-hexylbenzene	.2190E+07	.1691E-02	.6764E-02	.8981E+01
TIME		= 209.4906	[days]	
TOTAL MASS OF HYDROCARBON		= .41469E+05	[kg]	
TOTAL MASS IN VAPOR PHASE		= .14929E+03	[kg]	
TOTAL MASS IN OIL PHASE		= .70552E+04	[kg]	
TOTAL MASS IN WATER PHASE		= .65472E+03	[kg]	
TOTAL MASS IN SOLID PHASE		= .35951E+05	[kg]	
CHANGE IN HYDROCARBON MASS FOR TIME STEP		= .20376E+01	[%]	
CUMULATIVE CHANGE IN HYDROCARBON		= .77731E+02	[%]	
HYDROCARBON MASS PER SOIL MASS		= .17004E+03	[mg/kg]	

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.5185E+05	.1176E-01	.4704E-01	.2126E+00
2-methylheptane	.0000E+00	.1931E-02	.7725E-02	.0000E+00
n-octane	.1827E+05	.7480E-02	.2992E-01	.7492E-01
p-xylene	.2456E+07	.1908E+00	.7631E+00	.1007E+02
3,3,4-trimethylhexane	.4599E+06	.4946E-01	.1978E+00	.1886E+01
3,3,5-trimethylheptane	.1723E+07	.7131E-01	.2853E+00	.7067E+01
n-propylbenzene	.6117E+07	.2033E+00	.8132E+00	.2508E+02
1,3,5-trimethylbenzene	.3512E+07	.2825E-01	.1130E+00	.1440E+02
1,2,4-trimethylbenzene	.3546E+07	.2825E-01	.1130E+00	.1454E+02
methylpropylbenzene	.4978E+07	.6456E-01	.2582E+00	.2041E+02
dimethylethylbenzene	.6840E+07	.1706E-01	.6824E-01	.2805E+02
1,2,4,5-tetramethylbenze	.5121E+07	.9179E-01	.3671E+00	.2100E+02
n-dodecane	.3000E+07	.1007E+00	.4028E+00	.1230E+02
naphthalene	.1462E+07	.6207E-02	.2483E-01	.5995E+01
n-hexylbenzene	.2183E+07	.1869E-02	.7475E-02	.8951E+01
TIME		= 234.4906	[days]	
TOTAL MASS OF HYDROCARBON		= .37224E+05	[kg]	
TOTAL MASS IN VAPOR PHASE		= .13034E+03	[kg]	
TOTAL MASS IN OIL PHASE		= .42141E+04	[kg]	
TOTAL MASS IN WATER PHASE		= .54127E+03	[kg]	
TOTAL MASS IN SOLID PHASE		= .33080E+05	[kg]	
CHANGE IN HYDROCARBON MASS FOR TIME STEP		= .22796E+01	[%]	
CUMULATIVE CHANGE IN HYDROCARBON		= .80011E+02	[%]	
HYDROCARBON MASS PER SOIL MASS		= .15263E+03	[mg/kg]	

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.1900E+05	.6240E-02	.2496E-01	.7789E-01
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.5868E+04	.3865E-02	.1546E-01	.2406E-01
p-xylene	.1629E+07	.1847E+00	.7389E+00	.6681E+01
3,3,4-trimethylhexane	.3028E+06	.4889E-01	.1956E+00	.1242E+01
3,3,5-trimethylheptane	.1441E+07	.8808E-01	.3523E+00	.5907E+01
n-propylbenzene	.5138E+07	.2510E+00	.1004E+01	.2107E+02
1,3,5-trimethylbenzene	.3348E+07	.3832E-01	.1533E+00	.1373E+02
1,2,4-trimethylbenzene	.3383E+07	.3851E-01	.1541E+00	.1387E+02
methylpropylbenzene	.4669E+07	.9065E-01	.3626E+00	.1915E+02
dimethylethylbenzene	.6742E+07	.2397E-01	.9589E-01	.2765E+02
1,2,4,5-tetramethylbenze	.4625E+07	.1455E+00	.5820E+00	.1896E+02
n-dodecane	.2381E+07	.1933E+00	.7732E+00	.9763E+01
napthalene	.1366E+07	.9738E-02	.3895E-01	.5602E+01
n-hexylbenzene	.2173E+07	.2734E-02	.1094E-01	.8912E+01

TIME = 258.3001 [days]
 TOTAL MASS OF HYDROCARBON = .32670E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .13446E+03 [kg]
 TOTAL MASS IN OIL PHASE = .11659E+04 [kg]
 TOTAL MASS IN WATER PHASE = .44830E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .30921E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .24457E+01 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .82457E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .13396E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.5596E+04	.1906E-02	.7622E-02	.2294E-01
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.1919E-02	.7677E-02	.0000E+00
p-xylene	.1011E+07	.1199E+00	.4794E+00	.4146E+01
3,3,4-trimethylhexane	.1973E+06	.3441E-01	.1376E+00	.8092E+00
3,3,5-trimethylheptane	.1202E+07	.7792E-01	.3117E+00	.4928E+01
n-propylbenzene	.4234E+07	.2179E+00	.8718E+00	.1736E+02
1,3,5-trimethylbenzene	.3174E+07	.3695E-01	.1478E+00	.1302E+02
1,2,4-trimethylbenzene	.3208E+07	.3732E-01	.1493E+00	.1316E+02
methylpropylbenzene	.4362E+07	.9116E-01	.3646E+00	.1789E+02
dimethylethylbenzene	.6635E+07	.2404E-01	.9618E-01	.2721E+02
1,2,4,5-tetramethylbenze	.4048E+07	.1720E+00	.6879E+00	.1660E+02
n-dodecane	.1208E+07	.3843E+00	.1537E+01	.4954E+01
napthalene	.1220E+07	.1092E-01	.4370E-01	.5002E+01
n-hexylbenzene	.2163E+07	.2868E-02	.1147E-01	.8870E+01

TIME = 280.9759 [days]
 TOTAL MASS OF HYDROCARBON = .30212E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .12384E+03 [kg]
 TOTAL MASS IN OIL PHASE = .60177E+03 [kg]
 TOTAL MASS IN WATER PHASE = .38854E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .29098E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .13198E+01 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .83776E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .12388E+03 [mg/kg]

SPECIES	SPECIES	WELL GAS	EQUIL. GAS	SPECIES MASS
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	MASS [g]	CONCEN. [g/m^3]	CONCEN. [g/m^3]	PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.1344E-02	.5375E-02	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.7097E+06	.5381E-01	.2152E+00	.2910E+01
3,3,4-trimethylhexane	.1567E+06	.1758E-01	.7032E-01	.6427E+00
3,3,5-trimethylheptane	.1097E+07	.4559E-01	.1823E+00	.4497E+01
n-propylbenzene	.3727E+07	.1229E+00	.4915E+00	.1528E+02
1,3,5-trimethylbenzene	.3058E+07	.2267E-01	.9066E-01	.1254E+02
1,2,4-trimethylbenzene	.3092E+07	.2292E-01	.9167E-01	.1268E+02
methylpropylbenzene	.4201E+07	.5644E-01	.2258E+00	.1723E+02
dimethylethylbenzene	.6563E+07	.1515E-01	.6059E-01	.2691E+02
1,2,4,5-tetramethylbenze	.3737E+07	.1068E+00	.4274E+00	.1532E+02
n-dodecane	.6447E+06	.2462E+00	.9847E+00	.2644E+01
napthalene	.1068E+07	.6332E-02	.2533E-01	.4378E+01
n-hexylbenzene	.2158E+07	.1832E-02	.7328E-02	.8847E+01
time step reduced				

TIME = 291.1800 [days]
 TOTAL MASS OF HYDROCARBON = .28859E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .28898E+03 [kg]
 TOTAL MASS IN OIL PHASE = .00000E+00 [kg]
 TOTAL MASS IN WATER PHASE = .35522E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .28215E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .72669E+00 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .84503E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .11833E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.5589E+06	.4271E-01	.1708E+00	.2292E+01
3,3,4-trimethylhexane	.1506E+06	.1712E-01	.6849E-01	.6174E+00
3,3,5-trimethylheptane	.1080E+07	.4537E-01	.1815E+00	.4430E+01
n-propylbenzene	.3470E+07	.1155E+00	.4619E+00	.1423E+02
1,3,5-trimethylbenzene	.2984E+07	.2218E-01	.8871E-01	.1224E+02
1,2,4-trimethylbenzene	.3018E+07	.2245E-01	.8979E-01	.1237E+02
methylpropylbenzene	.4149E+07	.5647E-01	.2259E+00	.1701E+02
dimethylethylbenzene	.6519E+07	.1509E-01	.6038E-01	.2673E+02
1,2,4,5-tetramethylbenze	.3628E+07	.1107E+00	.4428E+00	.1488E+02
n-dodecane	.2169E+06	.1246E+01	.4983E+01	.8893E+00
napthalene	.9298E+06	.5776E-02	.2310E-01	.3813E+01
n-hexylbenzene	.2155E+07	.1847E-02	.7387E-02	.8837E+01

TIME = 293.7310 [days]
 TOTAL MASS OF HYDROCARBON = .28409E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .12921E+03 [kg]
 TOTAL MASS IN OIL PHASE = .00000E+00 [kg]
 TOTAL MASS IN WATER PHASE = .34807E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .27932E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .24141E+00 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .84744E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .11649E+03 [mg/kg]

SPECIES	SPECIES MASS	WELL GAS CONCEN.	EQUIL. GAS CONCEN.	SPECIES MASS PER SOIL MASS
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	[g]	[g/m^3]	[g/m^3]	[mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.5293E+06	.4045E-01	.1618E+00	.2170E+01
3,3,4-trimethylhexane	.1422E+06	.1617E-01	.6469E-01	.5831E+00
3,3,5-trimethylheptane	.1057E+07	.4441E-01	.1776E+00	.4336E+01
n-propylbenzene	.3395E+07	.1130E+00	.4519E+00	.1392E+02
1,3,5-trimethylbenzene	.2967E+07	.2205E-01	.8821E-01	.1217E+02
1,2,4-trimethylbenzene	.3001E+07	.2232E-01	.8929E-01	.1230E+02
methylpropylbenzene	.4117E+07	.5604E-01	.2242E+00	.1688E+02
dimethylethylbenzene	.6508E+07	.1507E-01	.6028E-01	.2668E+02
1,2,4,5-tetramethylbenzene	.3566E+07	.1088E+00	.4352E+00	.1462E+02
n-dodecane	.5478E+05	.3146E+00	.1259E+01	.2246E+00
napthalene	.9169E+06	.5695E-02	.2278E-01	.3760E+01
n-hexylbenzene	.2154E+07	.1846E-02	.7383E-02	.8833E+01

TIME = 297.5576 [days]
 TOTAL MASS OF HYDROCARBON = .27944E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .83292E+02 [kg]
 TOTAL MASS IN OIL PHASE = .00000E+00 [kg]
 TOTAL MASS IN WATER PHASE = .33810E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .27522E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .25001E+00 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .84994E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .11458E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.4879E+06	.3728E-01	.1491E+00	.2000E+01
3,3,4-trimethylhexane	.1307E+06	.1486E-01	.5945E-01	.5359E+00
3,3,5-trimethylheptane	.1024E+07	.4301E-01	.1720E+00	.4199E+01
n-propylbenzene	.3286E+07	.1093E+00	.4374E+00	.1348E+02
1,3,5-trimethylbenzene	.2942E+07	.2187E-01	.8747E-01	.1206E+02
1,2,4-trimethylbenzene	.2976E+07	.2214E-01	.8854E-01	.1220E+02
methylpropylbenzene	.4070E+07	.5540E-01	.2216E+00	.1669E+02
dimethylethylbenzene	.6491E+07	.1503E-01	.6012E-01	.2662E+02
1,2,4,5-tetramethylbenzene	.3475E+07	.1060E+00	.4241E+00	.1425E+02
n-dodecane	.1007E+05	.5785E-01	.2314E+00	.4130E-01
napthalene	.8974E+06	.5575E-02	.2230E-01	.3680E+01
n-hexylbenzene	.2152E+07	.1844E-02	.7378E-02	.8826E+01

TIME = 303.2974 [days]
 TOTAL MASS OF HYDROCARBON = .27324E+05 [kg]
 TOTAL MASS IN VAPOR PHASE = .70229E+02 [kg]
 TOTAL MASS IN OIL PHASE = .00000E+00 [kg]
 TOTAL MASS IN WATER PHASE = .32402E+03 [kg]
 TOTAL MASS IN SOLID PHASE = .26930E+05 [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP = .33258E+00 [%]
 CUMULATIVE CHANGE IN HYDROCARBON = .85327E+02 [%]
 HYDROCARBON MASS PER SOIL MASS = .11204E+03 [mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
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isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.4316E+06	.3298E-01	.1319E+00	.1770E+01
3,3,4-trimethylhexane	.1154E+06	.1313E-01	.5251E-01	.4733E+00
3,3,5-trimethylheptane	.9765E+06	.4101E-01	.1640E+00	.4004E+01
n-propylbenzene	.3129E+07	.1041E+00	.4164E+00	.1283E+02
1,3,5-trimethylbenzene	.2905E+07	.2159E-01	.8636E-01	.1191E+02
1,2,4-trimethylbenzene	.2938E+07	.2186E-01	.8742E-01	.1205E+02
methylpropylbenzene	.4001E+07	.5446E-01	.2178E+00	.1640E+02
dimethylethylbenzene	.6466E+07	.1497E-01	.5989E-01	.2651E+02
1,2,4,5-tetramethylbenze	.3344E+07	.1020E+00	.4081E+00	.1371E+02
n-dodecane	.0000E+00	.8685E-02	.3474E-01	.0000E+00
napthalene	.8683E+06	.5394E-02	.2157E-01	.3560E+01
n-hexylbenzene	.2150E+07	.1842E-02	.7369E-02	.8816E+01

TIME	=	311.9070	[days]
TOTAL MASS OF HYDROCARBON	=	.26456E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.65768E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.30444E+03	[kg]
TOTAL MASS IN SOLID PHASE	=	.26086E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.46625E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.85793E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.10848E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.3589E+06	.2742E-01	.1097E+00	.1472E+01
3,3,4-trimethylhexane	.9632E+05	.1095E-01	.4382E-01	.3950E+00
3,3,5-trimethylheptane	.9099E+06	.3821E-01	.1528E+00	.3731E+01
n-propylbenzene	.2906E+07	.9668E-01	.3867E+00	.1191E+02
1,3,5-trimethylbenzene	.2849E+07	.2117E-01	.8470E-01	.1168E+02
1,2,4-trimethylbenzene	.2882E+07	.2144E-01	.8575E-01	.1182E+02
methylpropylbenzene	.3899E+07	.5307E-01	.2123E+00	.1599E+02
dimethylethylbenzene	.6429E+07	.1489E-01	.5955E-01	.2636E+02
1,2,4,5-tetramethylbenze	.3156E+07	.9630E-01	.3852E+00	.1294E+02
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.8247E+06	.5123E-02	.2049E-01	.3381E+01
n-hexylbenzene	.2146E+07	.1839E-02	.7357E-02	.8801E+01

TIME	=	324.8216	[days]
TOTAL MASS OF HYDROCARBON	=	.25245E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.59828E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.27803E+03	[kg]
TOTAL MASS IN SOLID PHASE	=	.24907E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.65044E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.86444E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.10351E+03	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00

2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.2715E+06	.2075E-01	.8299E-01	.1113E+01
3,3,4-trimethylhexane	.7423E+05	.8441E-02	.3377E-01	.3044E+00
3,3,5-trimethylheptane	.8198E+06	.3443E-01	.1377E+00	.3361E+01
n-propylbenzene	.2598E+07	.8646E-01	.3458E+00	.1065E+02
1,3,5-trimethylbenzene	.2765E+07	.2055E-01	.8221E-01	.1134E+02
1,2,4-trimethylbenzene	.2798E+07	.2081E-01	.8324E-01	.1147E+02
methylpropylbenzene	.3751E+07	.5105E-01	.2042E+00	.1538E+02
dimethylethylbenzene	.6372E+07	.1475E-01	.5902E-01	.2613E+02
1,2,4,5-tetramethylbenze	.2895E+07	.8834E-01	.3533E+00	.1187E+02
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.7596E+06	.4719E-02	.1888E-01	.3115E+01
n-hexylbenzene	.2141E+07	.1834E-02	.7337E-02	.8778E+01

TIME	=	344.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.23602E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.52281E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.24380E+03	[kg]
TOTAL MASS IN SOLID PHASE	=	.23306E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.88238E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.87326E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.96776E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.1772E+06	.1573E-01	.6294E-01	.7264E+00
3,3,4-trimethylhexane	.5130E+05	.6781E-02	.2712E-01	.2103E+00
3,3,5-trimethylheptane	.7037E+06	.3435E-01	.1374E+00	.2886E+01
n-propylbenzene	.2193E+07	.8480E-01	.3392E+00	.8990E+01
1,3,5-trimethylbenzene	.2641E+07	.2281E-01	.9125E-01	.1083E+02
1,2,4-trimethylbenzene	.2672E+07	.2310E-01	.9241E-01	.1096E+02
methylpropylbenzene	.3539E+07	.5598E-01	.2239E+00	.1451E+02
dimethylethylbenzene	.6284E+07	.1691E-01	.6766E-01	.2577E+02
1,2,4,5-tetramethylbenze	.2545E+07	.9027E-01	.3611E+00	.1044E+02
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.6636E+06	.4791E-02	.1917E-01	.2721E+01
n-hexylbenzene	.2132E+07	.2124E-02	.8495E-02	.8743E+01

TIME	=	369.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.21634E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.44025E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.20415E+03	[kg]
TOTAL MASS IN SOLID PHASE	=	.21386E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.10565E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.88383E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.88708E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00

- benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.9440E+05	.1082E-01	.4328E-01	.3871E+00
3,3,4-trimethylhexane	.3250E+05	.5545E-02	.2218E-01	.1333E+00
3,3,5-trimethylheptane	.5801E+06	.3654E-01	.1462E+00	.2379E+01
n-propylbenzene	.1728E+07	.8625E-01	.3450E+00	.7086E+01
1,3,5-trimethylbenzene	.2470E+07	.2753E-01	.1101E+00	.1013E+02
1,2,4-trimethylbenzene	.2500E+07	.2789E-01	.1116E+00	.1025E+02
methylpropylbenzene	.3275E+07	.6687E-01	.2675E+00	.1343E+02
dimethylethylbenzene	.6161E+07	.2140E-01	.8560E-01	.2526E+02
1,2,4,5-tetramethylbenzene	.2146E+07	.9819E-01	.3928E+00	.8797E+01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.5274E+06	.4914E-02	.1966E-01	.2162E+01
n-hexylbenzene	.2121E+07	.2726E-02	.1090E-01	.8696E+01

TIME	=	394.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.19692E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.36709E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.16611E+03	[kg]
TOTAL MASS IN SOLID PHASE	=	.19489E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.10428E+01	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.89425E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.80746E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.4061E+05	.4654E-02	.1862E-01	.1665E+00
3,3,4-trimethylhexane	.2057E+05	.3508E-02	.1403E-01	.8433E-01
3,3,5-trimethylheptane	.4779E+06	.3010E-01	.1204E+00	.1960E+01
n-propylbenzene	.1298E+07	.6479E-01	.2591E+00	.5322E+01
1,3,5-trimethylbenzene	.2271E+07	.2532E-01	.1013E+00	.9313E+01
1,2,4-trimethylbenzene	.2300E+07	.2567E-01	.1027E+00	.9432E+01
methylpropylbenzene	.3013E+07	.6152E-01	.2461E+00	.1235E+02
dimethylethylbenzene	.6013E+07	.2089E-01	.8354E-01	.2466E+02
1,2,4,5-tetramethylbenzene	.1781E+07	.8150E-01	.3260E+00	.7302E+01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.3689E+06	.3437E-02	.1375E-01	.1513E+01
n-hexylbenzene	.2108E+07	.2710E-02	.1084E-01	.8644E+01

TIME	=	419.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.17930E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.30666E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.13483E+03	[kg]
TOTAL MASS IN SOLID PHASE	=	.17764E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.94639E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.90372E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.73519E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00

n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.1476E+05	.1691E-02	.6765E-02	.6050E-01
3,3,4-trimethylhexane	.1300E+05	.2218E-02	.8871E-02	.5331E-01
3,3,5-trimethylheptane	.3936E+06	.2479E-01	.9917E-01	.1614E+01
n-propylbenzene	.9437E+06	.4710E-01	.1884E+00	.3870E+01
1,3,5-trimethylbenzene	.2066E+07	.2303E-01	.9212E-01	.8470E+01
1,2,4-trimethylbenzene	.2094E+07	.2336E-01	.9344E-01	.8585E+01
methylpropylbenzene	.2761E+07	.5637E-01	.2255E+00	.1132E+02
dimethylethylbenzene	.5851E+07	.2032E-01	.8130E-01	.2399E+02
1,2,4,5-tetramethylbenzene	.1463E+07	.6696E-01	.2679E+00	.6000E+01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.2353E+06	.2192E-02	.8768E-02	.9646E+00
n-hexylbenzene	.2095E+07	.2692E-02	.1077E-01	.8589E+01

TIME	=	444.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.16318E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.25610E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.10931E+03	[kg]
TOTAL MASS IN SOLID PHASE	=	.16183E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.86575E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.91238E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.66909E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.4143E+04	.4749E-03	.1900E-02	.1699E-01
3,3,4-trimethylhexane	.8208E+04	.1400E-02	.5601E-02	.3366E-01
3,3,5-trimethylheptane	.3240E+06	.2041E-01	.8163E-01	.1328E+01
n-propylbenzene	.6580E+06	.3284E-01	.1314E+00	.2698E+01
1,3,5-trimethylbenzene	.1853E+07	.2066E-01	.8263E-01	.7598E+01
1,2,4-trimethylbenzene	.1880E+07	.2097E-01	.8390E-01	.7708E+01
methylpropylbenzene	.2518E+07	.5141E-01	.2056E+00	.1032E+02
dimethylethylbenzene	.5673E+07	.1971E-01	.7882E-01	.2326E+02
1,2,4,5-tetramethylbenzene	.1187E+07	.5433E-01	.2173E+00	.4867E+01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.1320E+06	.1230E-02	.4921E-02	.5413E+00
n-hexylbenzene	.2080E+07	.2674E-02	.1070E-01	.8530E+01

TIME	=	469.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.14831E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.21330E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.88744E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.14721E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.79804E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.92036E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.60815E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00

-	2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
	n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
	p-xylene	.0000E+00	.3053E-03	.1221E-02	.0000E+00
	3,3,4-trimethylhexane	.5175E+04	.8827E-03	.3531E-02	.2122E-01
-	3,3,5-trimethylheptane	.2665E+06	.1679E-01	.6716E-01	.1093E+01
-	n-propylbenzene	.4347E+06	.2170E-01	.8678E-01	.1782E+01
	1,3,5-trimethylbenzene	.1633E+07	.1821E-01	.7284E-01	.6698E+01
	1,2,4-trimethylbenzene	.1659E+07	.1851E-01	.7404E-01	.6803E+01
-	methylpropylbenzene	.2282E+07	.4660E-01	.1864E+00	.9358E+01
	dimethylethylbenzene	.5476E+07	.1902E-01	.7608E-01	.2245E+02
	1,2,4,5-tetramethylbenze	.9479E+06	.4338E-01	.1735E+00	.3887E+01
	n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
	napthalene	.6163E+05	.5742E-03	.2297E-02	.2527E+00
--	n-hexylbenzene	.2065E+07	.2654E-02	.1062E-01	.8467E+01

	TIME	=	494.1934	[days]
	TOTAL MASS OF HYDROCARBON	=	.13456E+05	[kg]
-	TOTAL MASS IN VAPOR PHASE	=	.17719E+02	[kg]
	TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
	TOTAL MASS IN WATER PHASE	=	.72593E+02	[kg]
	TOTAL MASS IN SOLID PHASE	=	.13366E+05	[kg]
-	CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.73857E+00	[%]
	CUMULATIVE CHANGE IN HYDROCARBON	=	.92774E+02	[%]
	HYDROCARBON MASS PER SOIL MASS	=	.55175E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
-	isopentane	.0000E+00	.0000E+00	.0000E+00
	n-pentane	.0000E+00	.0000E+00	.0000E+00
	2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00
	n-hexane	.0000E+00	.0000E+00	.0000E+00
-	benzene	.0000E+00	.0000E+00	.0000E+00
	2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00
	n-heptane	.0000E+00	.0000E+00	.0000E+00
	toluene	.0000E+00	.0000E+00	.0000E+00
-	2-methylheptane	.0000E+00	.0000E+00	.0000E+00
-	n-octane	.0000E+00	.0000E+00	.0000E+00
	p-xylene	.0000E+00	.0000E+00	.0000E+00
	3,3,4-trimethylhexane	.3257E+04	.5555E-03	.2222E-02
	3,3,5-trimethylheptane	.2192E+06	.1381E-01	.5522E-01
-	n-propylbenzene	.2679E+06	.1337E-01	.5349E-01
	1,3,5-trimethylbenzene	.1410E+07	.1571E-01	.6286E-01
	1,2,4-trimethylbenzene	.1434E+07	.1600E-01	.6399E-01
-	methylpropylbenzene	.2054E+07	.4193E-01	.1677E+00
	dimethylethylbenzene	.5257E+07	.1826E-01	.7304E-01
-	1,2,4,5-tetramethylbenze	.7423E+06	.3397E-01	.1359E+00
	n-dodecane	.0000E+00	.0000E+00	.0000E+00
	napthalene	.2176E+05	.2028E-03	.8111E-03
	n-hexylbenzene	.2048E+07	.2633E-02	.1053E-01

-	TIME	=	519.1934	[days]
	TOTAL MASS OF HYDROCARBON	=	.12170E+05	[kg]
	TOTAL MASS IN VAPOR PHASE	=	.14645E+02	[kg]
	TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
-	TOTAL MASS IN WATER PHASE	=	.59745E+02	[kg]
	TOTAL MASS IN SOLID PHASE	=	.12095E+05	[kg]
	CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.69085E+00	[%]
	CUMULATIVE CHANGE IN HYDROCARBON	=	.93465E+02	[%]
-	HYDROCARBON MASS PER SOIL MASS	=	.49900E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
-	isopentane	.0000E+00	.0000E+00	.0000E+00
	n-pentane	.0000E+00	.0000E+00	.0000E+00
-	2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00
	n-hexane	.0000E+00	.0000E+00	.0000E+00
-	benzene	.0000E+00	.0000E+00	.0000E+00
	2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00
-	n-heptane	.0000E+00	.0000E+00	.0000E+00
	toluene	.0000E+00	.0000E+00	.0000E+00
	2-methylheptane	.0000E+00	.0000E+00	.0000E+00
-	n-octane	.0000E+00	.0000E+00	.0000E+00

p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.2045E+04	.3489E-03	.1395E-02	.8386E-02
3,3,5-trimethylheptane	.1800E+06	.1134E-01	.4537E-01	.7382E+00
n-propylbenzene	.1506E+06	.7519E-02	.3008E-01	.6177E+00
1,3,5-trimethylbenzene	.1184E+07	.1320E-01	.5281E-01	.4856E+01
1,2,4-trimethylbenzene	.1207E+07	.1347E-01	.5387E-01	.4949E+01
methylpropylbenzene	.1831E+07	.3739E-01	.1496E+00	.7509E+01
dimethylethylbenzene	.5013E+07	.1741E-01	.6964E-01	.2055E+02
1,2,4,5-tetramethylbenzene	.5674E+06	.2597E-01	.1039E+00	.2326E+01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.4665E+04	.4347E-04	.1739E-03	.1913E-01
n-hexylbenzene	.2030E+07	.2609E-02	.1044E-01	.8323E+01

TIME	=	544.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.10960E+05	[kg]
TOTAL MASS IN VAPOR PHASE	=	.12042E+02	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.49318E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.10899E+05	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.64946E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.94114E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.44941E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.1281E+04	.2185E-03	.8741E-03	.5253E-02
3,3,5-trimethylheptane	.1478E+06	.9309E-02	.3723E-01	.6059E+00
n-propylbenzene	.7516E+05	.3751E-02	.1501E-01	.3082E+00
1,3,5-trimethylbenzene	.9635E+06	.1074E-01	.4297E-01	.3951E+01
1,2,4-trimethylbenzene	.9841E+06	.1098E-01	.4392E-01	.4035E+01
methylpropylbenzene	.1616E+07	.3298E-01	.1319E+00	.6624E+01
dimethylethylbenzene	.4742E+07	.1647E-01	.6588E-01	.1944E+02
1,2,4,5-tetramethylbenzene	.4211E+06	.1927E-01	.7710E-01	.1727E+01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.7352E-04	.2941E-03	.0000E+00
n-hexylbenzene	.2010E+07	.2583E-02	.1033E-01	.8240E+01

TIME	=	569.1934	[days]
TOTAL MASS OF HYDROCARBON	=	.98242E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.98365E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.40634E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.97737E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.61001E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.94724E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.40283E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.3930E-03	.1572E-02	.0000E+00

3,3,5-trimethylheptane	.1212E+06	.8014E-02	.3205E-01	.4968E+00
n-propylbenzene	.3210E+05	.1683E-02	.6730E-02	.1316E+00
1,3,5-trimethylbenzene	.7548E+06	.8835E-02	.3534E-01	.3095E+01
1,2,4-trimethylbenzene	.7732E+06	.9059E-02	.3624E-01	.3170E+01
methylpropylbenzene	.1408E+07	.3018E-01	.1207E+00	.5773E+01
dimethylethylbenzene	.4446E+07	.1621E-01	.6485E-01	.1823E+02
1,2,4,5-tetramethylbenze	.3021E+06	.1452E-01	.5807E-01	.1239E+01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1987E+07	.2682E-02	.1073E-01	.8148E+01

TIME	=	593.0029	[days]
TOTAL MASS OF HYDROCARBON	=	.87466E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.79915E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.33069E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.87056E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.57863E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.95303E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.35865E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.1000E+06	.6616E-02	.2646E-01	.4101E+00
n-propylbenzene	.1062E+05	.5568E-03	.2227E-02	.4357E-01
1,3,5-trimethylbenzene	.5610E+06	.6567E-02	.2627E-01	.2300E+01
1,2,4-trimethylbenzene	.5769E+06	.6758E-02	.2703E-01	.2365E+01
methylpropylbenzene	.1210E+07	.2594E-01	.1037E+00	.4961E+01
dimethylethylbenzene	.4118E+07	.1502E-01	.6008E-01	.1689E+02
1,2,4,5-tetramethylbenze	.2077E+06	.9980E-02	.3992E-01	.8515E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1962E+07	.2649E-02	.1059E-01	.8047E+01

TIME	=	615.6786	[days]
TOTAL MASS OF HYDROCARBON	=	.77613E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.64731E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.26739E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.77280E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.52913E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.95832E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.31824E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.8312E+05	.5498E-02	.2199E-01	.3408E+00
n-propylbenzene	.2555E+04	.1339E-03	.5355E-03	.1047E-01

1,3,5-trimethylbenzene	.3960E+06	.4635E-02	.1854E-01	.1624E+01
1,2,4-trimethylbenzene	.4091E+06	.4793E-02	.1917E-01	.1677E+01
methylpropylbenzene	.1026E+07	.2200E-01	.8799E-01	.4207E+01
dimethylethylbenzene	.3772E+07	.1376E-01	.5503E-01	.1547E+02
1,2,4,5-tetramethylbenzene	.1369E+06	.6581E-02	.2632E-01	.5615E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
naphthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1936E+07	.2612E-02	.1045E-01	.7936E+01

TIME	=	637.2746	[days]
TOTAL MASS OF HYDROCARBON	=	.68549E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.52069E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.21396E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.68283E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.48669E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.96319E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.28108E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.6950E+05	.4597E-02	.1839E-01	.2850E+00
n-propylbenzene	.0000E+00	.1348E-03	.5393E-03	.0000E+00
1,3,5-trimethylbenzene	.2612E+06	.3057E-02	.1223E-01	.1071E+01
1,2,4-trimethylbenzene	.2714E+06	.3180E-02	.1272E-01	.1113E+01
methylpropylbenzene	.8553E+06	.1833E-01	.7334E-01	.3507E+01
dimethylethylbenzene	.3406E+07	.1242E-01	.4969E-01	.1397E+02
1,2,4,5-tetramethylbenzene	.8539E+05	.4104E-02	.1641E-01	.3502E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
naphthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1906E+07	.2572E-02	.1029E-01	.7815E+01

TIME	=	657.8422	[days]
TOTAL MASS OF HYDROCARBON	=	.60205E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.41518E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.16932E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.59994E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.44808E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.96767E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.24687E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.5842E+05	.3864E-02	.1546E-01	.2395E+00
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.1572E+06	.1840E-02	.7359E-02	.6444E+00
1,2,4-trimethylbenzene	.1646E+06	.1929E-02	.7715E-02	.6750E+00

methylpropylbenzene	.6968E+06	.1494E-01	.5975E-01	.2857E+01
dimethylethylbenzene	.3021E+07	.1102E-01	.4408E-01	.1239E+02
1,2,4,5-tetramethylbenze	.4933E+05	.2370E-02	.9482E-02	.2023E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1873E+07	.2528E-02	.1011E-01	.7679E+01

TIME	=	677.4303	[days]
TOTAL MASS OF HYDROCARBON	=	.52440E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.32649E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.13197E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.52275E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.41699E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.97184E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.21502E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.4932E+05	.3262E-02	.1305E-01	.2022E+00
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.8243E+05	.9649E-03	.3860E-02	.3380E+00
1,2,4-trimethylbenzene	.8728E+05	.1023E-02	.4090E-02	.3579E+00
methylpropylbenzene	.5497E+06	.1178E-01	.4713E-01	.2254E+01
dimethylethylbenzene	.2615E+07	.9536E-02	.3815E-01	.1072E+02
1,2,4,5-tetramethylbenze	.2539E+05	.1220E-02	.4880E-02	.1041E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1835E+07	.2477E-02	.9907E-02	.7525E+01

TIME	=	696.0857	[days]
TOTAL MASS OF HYDROCARBON	=	.45208E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.25274E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.10132E+02	[kg]
TOTAL MASS IN SOLID PHASE	=	.45081E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.38836E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.97572E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.18537E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.4177E+05	.2763E-02	.1105E-01	.1713E+00
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.3492E+05	.4087E-03	.1635E-02	.1432E+00
1,2,4-trimethylbenzene	.3759E+05	.4404E-03	.1762E-02	.1541E+00
methylpropylbenzene	.4146E+06	.8888E-02	.3555E-01	.1700E+01
dimethylethylbenzene	.2189E+07	.7985E-02	.3194E-01	.8978E+01

1,2,4,5-tetramethylbenze	.1095E+05	.5261E-03	.2104E-02	.4489E-01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
naphthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1792E+07	.2418E-02	.9672E-02	.7346E+01

TIME	=	713.8527	[days]
TOTAL MASS OF HYDROCARBON	=	.38449E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.19185E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.76421E+01	[kg]
TOTAL MASS IN SOLID PHASE	=	.38353E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.36296E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.97935E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.15765E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.3543E+05	.2344E-02	.9375E-02	.1453E+00
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.1009E+05	.1181E-03	.4726E-03	.4138E-01
1,2,4-trimethylbenzene	.1120E+05	.1312E-03	.5247E-03	.4591E-01
methylpropylbenzene	.2934E+06	.6289E-02	.2516E-01	.1203E+01
dimethylethylbenzene	.1751E+07	.6386E-02	.2555E-01	.7180E+01
1,2,4,5-tetramethylbenze	.3485E+04	.1675E-03	.6699E-03	.1429E-01
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
naphthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1740E+07	.2349E-02	.9395E-02	.7135E+01

TIME	=	730.7737	[days]
TOTAL MASS OF HYDROCARBON	=	.32112E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.14168E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.55996E+01	[kg]
TOTAL MASS IN SOLID PHASE	=	.32042E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.34026E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.98276E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.13167E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.3005E+05	.1988E-02	.7951E-02	.1232E+00
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.1065E+04	.1247E-04	.4988E-04	.4368E-02
1,2,4-trimethylbenzene	.1307E+04	.1531E-04	.6124E-04	.5358E-02
methylpropylbenzene	.1887E+06	.4044E-02	.1618E-01	.7736E+00
dimethylethylbenzene	.1311E+07	.4781E-02	.1912E-01	.5375E+01
1,2,4,5-tetramethylbenze	.5674E+03	.2727E-04	.1091E-03	.2327E-02
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00

napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1679E+07	.2266E-02	.9062E-02	.6883E+01

TIME	=	746.8890	[days]
TOTAL MASS OF HYDROCARBON	=	.26161E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.10019E+01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.38723E+01	[kg]
TOTAL MASS IN SOLID PHASE	=	.26112E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.31957E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.98595E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.10727E+02	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.2539E+05	.1680E-02	.6719E-02	.1041E+00
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
methylpropylbenzene	.1035E+06	.2220E-02	.8879E-02	.4246E+00
dimethylethylbenzene	.8843E+06	.3225E-02	.1290E-01	.3626E+01
1,2,4,5-tetramethylbenze	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1603E+07	.2163E-02	.8653E-02	.6572E+01

TIME	=	762.2368	[days]
TOTAL MASS OF HYDROCARBON	=	.20552E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.65693E+00	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.23520E+01	[kg]
TOTAL MASS IN SOLID PHASE	=	.20522E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.30119E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.98896E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.84273E+01	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.2124E+05	.1338E-02	.5353E-02	.8710E-01
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
nethylpropylbenzene	.4066E+05	.8302E-03	.3321E-02	.1667E+00
dimethylethylbenzene	.4887E+06	.1697E-02	.6790E-02	.2004E+01
1,2,4,5-tetramethylbenze	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1505E+07	.1934E-02	.7736E-02	.6170E+01

TIME	=	777.5847	[days]
TOTAL MASS OF HYDROCARBON	=	.15255E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.38350E+00	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.10712E+01	[kg]
TOTAL MASS IN SOLID PHASE	=	.15240E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.28447E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.99181E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.62551E+01	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.1717E+05	.1082E-02	.4327E-02	.7041E-01
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
methylpropylbenzene	.2540E+04	.5186E-04	.2075E-03	.1042E-01
dimethylethylbenzene	.1448E+06	.5028E-03	.2011E-02	.5935E+00
1,2,4,5-tetramethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1361E+07	.1749E-02	.6998E-02	.5581E+01

TIME	=	792.9325	[days]
TOTAL MASS OF HYDROCARBON	=	.10852E+04	[kg]
TOTAL MASS IN VAPOR PHASE	=	.24350E+00	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.48399E+00	[kg]
TOTAL MASS IN SOLID PHASE	=	.10844E+04	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.23646E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.99417E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.44496E+01	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m ³]	EQUIL. GAS CONCEN. [g/m ³]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.1223E+05	.7706E-03	.3083E-02	.5016E-01
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
methylpropylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
dimethylethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4,5-tetramethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.1073E+07	.1379E-02	.5516E-02	.4399E+01

TIME	=	808.2803	[days]
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TOTAL MASS OF HYDROCARBON	=	.56015E+03	[kg]
TOTAL MASS IN VAPOR PHASE	=	.12330E+00	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.24986E+00	[kg]
TOTAL MASS IN SOLID PHASE	=	.55978E+03	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.28192E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.99699E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.22969E+01	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.5973E+04	.3763E-03	.1505E-02	.2449E-01
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
methylpropylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
dimethylethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4,5-tetramethylbenze	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.5542E+06	.7123E-03	.2849E-02	.2272E+01

TIME	=	823.6282	[days]
TOTAL MASS OF HYDROCARBON	=	.37209E+02	[kg]
TOTAL MASS IN VAPOR PHASE	=	.10284E-01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.16569E-01	[kg]
TOTAL MASS IN SOLID PHASE	=	.37183E+02	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.28082E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.99980E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.15257E+00	[mg/kg]

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.6963E+03	.5264E-04	.2106E-03	.2855E-02
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
methylpropylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
dimethylethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4,5-tetramethylbenze	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.3651E+05	.5632E-04	.2253E-03	.1497E+00

.....FINAL RESULTS.....

TIME	=	823.6282	[days]
TOTAL MASS OF HYDROCARBON	=	.00000E+00	[kg]
TOTAL MASS IN VAPOR PHASE	=	.10284E-01	[kg]
TOTAL MASS IN OIL PHASE	=	.00000E+00	[kg]
TOTAL MASS IN WATER PHASE	=	.16569E-01	[kg]
TOTAL MASS IN SOLID PHASE	=	.37183E+02	[kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP	=	.28082E+00	[%]
CUMULATIVE CHANGE IN HYDROCARBON	=	.99980E+02	[%]
HYDROCARBON MASS PER SOIL MASS	=	.00000E+00	[mg/kg]

SPECIES	SPECIES MASS [g] IN			
	GAS	OIL	WATER	SOLID
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.4968E+01	.0000E+00	.2456E+00	.6911E+03
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
methylpropylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
dimethylethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4,5-tetramethylbenze	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.5316E+01	.0000E+00	.1632E+02	.3649E+05

SPECIES	SPECIES MASS [g]	WELL GAS CONCEN. [g/m^3]	EQUIL. GAS CONCEN. [g/m^3]	SPECIES MASS PER SOIL MASS [mg/kg]
isopentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-pentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylbutane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
benzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2,3-dimethylpentane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-heptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
toluene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2-methylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-octane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
p-xylene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,4-trimethylhexane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
3,3,5-trimethylheptane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-propylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,3,5-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4-trimethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
methylpropylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
dimethylethylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1,2,4,5-tetramethylbenze	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-dodecane	.0000E+00	.0000E+00	.0000E+00	.0000E+00
napthalene	.0000E+00	.0000E+00	.0000E+00	.0000E+00
n-hexylbenzene	.0000E+00	.0000E+00	.0000E+00	.0000E+00

Total number of time steps =	50
Total number of iterations =	401

Air Sparging Model for Predicting Groundwater Cleanup Rate

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Abstract

Groundwater air sparging has only recently been employed as a technology for the remediation of dissolved, volatile contaminants. The feasibility of implementing air sparging is, in part, dependent upon the time required to reach a desired cleanup goal. A simple, diffusive-flux-limited, mass transfer model is proposed as a quick screening method for estimating cleanup rate and time. The mass transfer of volatile contaminants from water to air appears to be diffusive-flux limited because the residence time of air bubbles in the groundwater does not allow equilibration as described by Henry's Law. The model predicts exponential cleanup rates based on remediation site parameters. Model predictions are compared with data from two groundwater air sparging remediation sites. The model results are coincident with measured groundwater concentrations from one of the sites, and provide a reasonable estimate of cleanup time for both sites.

Introduction

In recent years, at least 21 remediation sites have used groundwater air sparging with soil vapor extraction for in situ removal of volatile contaminants (Loden and Fan, 1992). Some investigators have suggested that the volatile contaminant removal rate with air sparging can be up to an order of magnitude greater than the use of soil vapor extraction (SVE) alone (Bohler, Brauns, Hotzl and Nahold, 1990). If most of the contaminant removal is due to air sparging, then cleanup time for a combined sparging and soil vapor extraction system is essentially a function of the air sparging contaminant transfer rate.

Sites that have featured air sparging have often met groundwater cleanup goals in less than one year (Ardito and Billings, 1990; Brown, Herman and Henry, 1991; Kresge and Dacey, 1991; Looney, Kaback and Corey, 1991; Marley, Walsh and Nangeroni, 1990). Some of these sites previously used SVE alone with limited success (Ardito and Billings, 1990; Marley et al., 1990).

Important criteria for selecting a remedial technology are cleanup rate and time. This paper proposes a simple analytical methodology for estimating groundwater cleanup rates and times. The method is applied to and compared with groundwater results from two air sparging sites for which adequate site and operating information were available (Marley et al., 1990; and Brown et al., 1991).

Background

Air sparging enhances the removal of volatile contaminants by injecting dispersed air bubbles into the groundwater. Figure 1 is a schematic diagram illustrating an air sparging system. As injected air bubbles rise through the saturated zone, dissolved volatile contaminants are transferred from the aqueous phase to the vapor phase by diffusion. Volatile contaminants released into the vadose zone are captured by the SVE system, which induces vapor flow toward a vacuum extraction well, removing contaminant vapors.

In general, air sparging is most successful at remediating groundwater when sites have the following characteristics:

- o water table conditions prevail;
- o soils are highly porous and permeable, without extensive clay layers above the air sparger;
- o the saturated zone soils have very little organic matter, and low contaminant sorption capacities;
- o contaminants are dissolved volatile organic compounds in groundwater;
- o the contaminants have high Henry's constants (around 10^{-3} atm-m³/mole) and/or high vapor pressures (above 100 mm Hg).

Methodology Overview

To date, there are no methods available for predicting groundwater cleanup rate or time with air sparging. To address the need for an air sparging model, a lumped parameter, diffusive-flux-limited model was proposed. The model states that the rate of contaminant mass transfer diffusing into the sparging bubbles is balanced by loss of dissolved phase contaminant from the groundwater. Vapor phase contaminants are assumed to be completely removed from the system by SVE once they reach the vadose zone. Thus, there is an ever-decreasing contaminant mass dissolved in the groundwater.

The lumped parameter model assumes that there is a concentration gradient around the sparging bubbles and an even distribution of bubbles within the "volume of influence" around the air sparger. The volume of influence is defined by the extent to which sparging bubbles penetrate the contaminated aquifer. Field-measured values for the radius of influence of sparging bubbles are used to estimate the volume of influence. The volume of influence defines the boundaries for the contaminant mass balance.

Assumptions

The model assumes idealized subsurface conditions, and constant air sparging operating parameters are as follows.

- o The subsurface has a high permeability and porosity typical of a sand or gravel, with low chemical sorption capacity.
- o The subsurface stratigraphy is homogeneous and isotropic with uniform porosity.
- o Contaminant removal rate and cleanup time are only dependent upon contaminant volatilization rate.
- o Sparging air bubbles are distributed evenly in the volume of influence around the air sparger.
- o There is complete mixing between the sparged volume of influence and the unsparged portion of the contaminant plume.

The model assumes that the only mechanism for contaminant removal is mass transfer. It is possible that other removal mechanisms, such as biodegradation, may also occur during sparging. Thus, application of this model is limited to groundwater environments that are nutrient poor.

For modeling purposes it is assumed that injected air bubbles are spherical as depicted in Figure 2. If air injection creates bubbles with an effective spherical diameter greater than the soil pore spaces, then it is possible that the bubble geometry is actually irregular as depicted in Figure 3.

The model also does not account for removal of pure phase chemical contaminants within the saturated zone or floating on the groundwater table.

Input Parameters

Estimation of contaminant removal rate and groundwater cleanup time with air sparging requires both measured and estimated input parameters.

Measured parameters:

- $C(t)$ = average groundwater contaminant concentration in the sparged plume;
 Q = total injected air flow rate into groundwater;
 t = time;
 d = fraction of a 24-hour day that the sparging system operates;
 H = depth of screen below groundwater table;
 R = radius of sparger openings;
 R_{oi} = radius of influence of the sparging bubbles; and
 n = average total porosity of soil.

The above parameters are easily measured, with the exception of the radius of influence of the sparging bubbles, and the initial groundwater

concentration.

Currently, there is no standard method for determining the radius of influence of an air sparger. Potential measurement methods include: measurement of groundwater mounding, dissolved oxygen distribution, and the use of tracer gases. As the injected air rises, it entrains the surrounding groundwater causing a mounding of the groundwater surface around the injection point. Some researchers have suggested that lateral extent of groundwater mounding can be used to define the radius of influence of the injected air (Brown, et al., 1991). Using the extent of groundwater mounding may overestimate the radius of influence of the sparging bubbles, because it is not clearly known which fraction of a mounded region would actually have rising air bubbles, and what portion would be primarily displaced groundwater. Radius of influence has also been estimated by dissolved oxygen (D.O.) measurements (Kresge and Dacey, 1991). However, D.O. may also overestimate the radius of influence of the sparging bubbles because oxygen is transferred from the air bubbles to groundwater that is probably circulated away from the air sparger. To date, there are no published studies on the use of tracer gases, such as helium or argon, to define the radius of influence. However, using tracer gases seems promising because, unlike oxygen, there are tracer gases that do not readily dissolve in water, and would only be detected in the sparging bubbles.

The initial the groundwater contaminant concentration in a contaminant plume will vary depending on distance of the monitoring point from the contaminant source, the direction of groundwater flow and the physical subsurface characteristics. To simplify model input values, the initial groundwater contaminant concentration is a plume area-weighted average of the contaminant concentration at the time when sparging is initiated.

Estimated Parameters and Suggested Estimation Methods:

- D = Contaminant diffusion coefficient in water: Most aqueous diffusion coefficients for non-polar, volatile organic compounds vary between 9×10^{-6} to 1.09×10^{-5} cm^2/s (Hayduk and Laudie, 1974). Thus, 1×10^{-5} cm^2/s is an adequate estimate.
- L = Diffusive distance around bubble (Figure 2): For the purposes of this model it is assumed that the diffusive distance is equal to the average effective radius of the bubble.
- r = Average effective radius of sparging bubble (Figure 2): Based on the size of the sparger opening. Orr (1966) provides an estimate of bubble radius, under low flow conditions for air injection into water.

$$r = 2R[6\sigma/((R)^2(\rho_{\text{water}} - \rho_{\text{air}})g)]^{1/3} \quad (1)$$

In the above relationship, R is the orifice diameter, σ is the air-water surface tension (0.0728 N/m), ρ_{water} is the density of water 1000 kg/m^3 , ρ_{air} is the density of air (1.29 kg/m^3 at 10°C), and g is the gravitational constant (9.81 m/sec^2). Typical effective radii may range from 0.5 to 2 mm.

S/V = Average effective surface to volume ratio of a bubble: This value is estimated from effective radius. The air bubble surface area to volume ratio is based on the effective radius of a bubble, r :

$$S/V = (4\pi r^2)/[(4/3)\pi r^3] = 3/r \quad (2)$$

v = Bubble terminal rise velocity: Small bubbles rising through water will rapidly reach a terminal rise velocity. In this model it is assumed that the subsurface has uniformly high porosity, thus, the terminal rise velocity in water alone is used as an estimate. For bubbles with radii between 0.4 and 10 mm, Falvey (1980) provided an estimate of the terminal rise velocity, v , in water as a function of buoyant and surface tension forces.

$$v = [1.04gr + (1.07\sigma)/(r \rho_{\text{water}})]^{1/2} \quad (3)$$

According to Falvey (1980) bubbles with radii ranging from 0.4 to 10 mm have a terminal rise velocity close to 0.25 m/sec.

V_s = Volume of water in the contaminant plume that is in contact with sparging bubbles. Air bubbles will be distributed as a rising plume around the sparger. V_s is the sum of the volume of influence around each sparger in a contaminant plume. The volume of influence around an air sparger only refers to the volume occupied by groundwater defined by the radius of influence, R_{oi} , of the sparger times the subsurface porosity, n . For simplicity, the volume of influence is considered to be a cylindrical volume around a sparging point of depth H (Figure 4). In addition, it is assumed that individual radii of influence do not overlap. For k spargers, the V is defined as:

$$V_s = k \pi R_{oi}^2 H n \quad (4)$$

f = Fraction of the contaminant plume sparged: This is based on the percentage of contaminant plume area that the radii of influence of all of the sparging wells cover. Figure 5 depicts an idealized grid of air injection points in a contaminant plume. The fraction of the plume sparged is equal to the total plume area minus the shaded area divided by the total plume area.

Model Development

The model development focuses on the concept of air bubble-scale diffusive flux of volatile contaminants. The microscale diffusive flux is then incorporated into an overall mass transfer of contaminants from the plume.

An injected air bubble's contaminant concentration reaching the groundwater surface, $C_{\text{air}}(t)$, is estimated by multiplying the diffusive flux, $J(t)$, by the ratio of a bubble's surface area to volume, S/V (equation 2), and the time, T , for a bubble to rise from the sparger to the groundwater surface.

$$C_{\text{air}}(t) = J(t)(S/V)T \quad (5)$$

The diffusive flux, $J(t)$, is a function of the contaminant concentration

gradient $(C(t)/L)$ into the sparging bubble:

$$J(t) = D[C(t)/L] \quad (6)$$

where D is the diffusion coefficient of the contaminant in water, L is the diffusive distance around the sparging bubble; and $C(t)$ is the groundwater contaminant concentration in the sparged zone.

Estimation of $C_{air}(t)$ also requires the time, T , it takes for bubbles to travel the distance H from the injection point to the groundwater surface at a terminal rise velocity of v (equation 3):

$$T = H/v \quad (7)$$

Substituting equations 6 and 7 into equation 5 yields:

$$C_{air}(t) = D (C(t)/L)(S/V)(H/v) \quad (8)$$

The instantaneous contaminant mass removal rate, $dM(t)/dt$, from the groundwater by air sparging is related to $C_{air}(t)$ and to the air injection flow rate in to the contaminant plume, Q :

$$dM(t)/dt = - C_{air}(t) Q \quad (9)$$

Assuming that all of the spargers have the same characteristics and are evenly distributed throughout the plume, equation 9 is modified by the fraction of the groundwater plume that is sparged, f , and the fraction of a 24-hour day that the sparging system is operated, d .

$$dM(t)/dt = - f d C_{air}(t) Q \quad (10)$$

The instantaneous contaminant mass removal rate can also be defined as the change in groundwater contaminant concentration per unit time and the volume of groundwater that is in contact with sparging bubbles, V_s :

$$dM(t)/dt = [dC(t)/dt] V_s \quad (11)$$

Relating equations 10 and 11 yields:

$$dC(t)/dt = - f d C_{air}(t) Q/V_s \quad (12)$$

Substituting equation 8 into equation 12 results in the following relationship:

$$dC(t)/dt = - f d (D/L) (S/V) (H/v) (Q/V_s) C(t) \quad (13)$$

Replacing part of this expression with:

$$B = f d (D/L) (S/V) (H/v) (Q/V_s) \quad (14)$$

yields:

$$dC(t)/dt = - B C(t) \quad (15)$$

The solution to equation 15 is a simple exponential decrease of concentration over time:

$$C(t) = C(0) e^{-B t} \quad (16)$$

Where $C(0)$ is the initial groundwater concentration. Equation 16 expresses the cleanup rate and can be used to estimate cleanup time for a groundwater plume with an initial concentration of $C(0)$ and the estimated and measured physical parameters used to determine B .

Implicit in the above model development is the assumption that the sparged water will mix with plume water surrounding it. Thus, the contaminant concentration in the plume $C(t)$ represents an average mixed plume concentration. Sparging the groundwater may cause local convective movement of groundwater around the sparger, much like the convective cells that occur in aeration basins. In addition, many groundwater sparging operations have pulsed air injection that may enhance water movement in and out of an individual sparger's volume of influence. Injected air displaces some of the water in the volume of influence. When the air injection ceases, groundwater will replace the volume occupied by air. This is likely to lead to mixing of sparged and unsparged groundwater. Thus, our assumption of "complete mixing" is a good approximation.

Application of Model

Case 1

The model was applied to a site described by Marley, Walsh, and Nanergoni (1990) where air sparging and soil vapor extraction were used to remove BTEX (benzene, toluene, ethylbenzene, and xylene) from groundwater contaminated with gasoline. The subsurface geology was described as fine to coarse sand with fine to medium gravel, with high permeability from the ground surface extending to 19 - 20 feet below. The permeable layer was underlain by less permeable, well sorted, dense sand. The groundwater was approximately 16' below grade. The site had 7 shallow and 6 deep air sparging wells. The shallow wells were screened 3-5 feet below the water table, with air sparging rates of 3-6 cubic feet per minute (cfm), operated 3 hours on and 9 hours off. Deeper sparging wells were screened 9-11 feet below the water table with air sparging rates of 2-6 cfm, operated 6 hours on and 6 hours off. The radius of influence around an air sparger was estimated to be 5 feet. There was one groundwater monitoring well within the contaminant plume. Groundwater from this well was analyzed for BTEX monthly.

A prediction of the groundwater cleanup time was made with the sparging model using input parameters listed in Table 1. The model-predicted estimates and measured groundwater concentrations (Marley et al., 1990) are illustrated in Figure 6. The model predicted that the groundwater would be remediated to less than 1 ppm BTEX in less than 15 days. Cleanup was actually achieved in less than 30 days, with the model showing close agreement with the groundwater concentration measured on the 12th day. In addition, the cleanup rate indicated by groundwater concentrations is reasonably matched by the model.

Case 2

In the second example, the model was applied to a case study by Brown, Herman and Henry (1991). The site was a former dry cleaning facility where groundwater was contaminated with tetrachloroethene (PCE), trichloroethene (TCE), dichloroethene (DCE), and undefined petroleum contaminants targeted by total petroleum hydrocarbons (TPH) measurements. Initial concentrations of PCE, TCE and DCE were quantified as volatile organic compounds (VOCs). VOC levels in the groundwater were measured at ten monitoring well locations prior to sparging, and 54 and 125 days after sparging was initiated. The 125-day groundwater samples were taken one week after the system was shut off, and had higher VOC concentrations than the 54-day samples. This may be due to the re-equilibration of the groundwater VOCs with VOCs sorbed to the soil. Initial VOC concentrations measured at 10 monitoring wells ranged from 0.014 to 41 mg/L, with an average concentration of 6.3 mg/L. For modeling purposes, the initial groundwater VOC concentration was assumed to be the average VOC concentration.

The subsurface geology was described as miscellaneous fill overlying relatively homogeneous Quaternary sediments (undefined sediments presumed to be sand and gravel). The air sparging and soil vapor extraction remediation system consisted of 7 combination sparging and SVE points, 1 SVE point alone and 7 air sparging points alone. The sparging points were screened 7-9 feet below the water table with an average air injection rate to each sparger of 16 cfm. A 50-foot radius of influence was assumed during the design of the sparger system. A measured radius of influence of 72 ft was based on groundwater mounding measurements.

Model input parameters for the second case are listed in Table 2. Two model simulations were performed on the data of Brown et al., 1991, listed as 2A and 2B in Table 2. Model predictions were compared with the average of measured groundwater contaminant concentrations for days 1, 54 and 128 in Figure 7. The first model simulation, 2A, assumed a 50 ft radius of influence and 100% of the plume in contact with sparging bubble (the higher curve on Figure 7), it appears that the model did not fit the Brown et al., 1991 data as well it fit the Marley et al., 1990 data in Case 1. The measured groundwater contaminant concentration decreased more rapidly on day 54 than the model predicted. However, the initial groundwater contaminant concentration measured had considerable spread. Thus the average initial groundwater contaminant concentration input into the model of 6.3 mg/L only approximates initial conditions. The model predictions did provide a reasonable estimate of the groundwater cleanup time. The model predicted that the groundwater would be remediated to less than 1 ppm VOCs in approximately 80 days.

The second model simulation was also plotted on Figure 7 (the lower curve). This fit assumed that: 1) the radius of influence, as measured by groundwater mounding was overestimated and should have been around 15 ft; 2) the smaller radius of influence covered only 25% of the plume; 3) there was mixing between the sparged and unsparged portion of the plume; and 4) that the higher 125-day groundwater monitoring data represents post-sparging re-equilibration with VOCs sorbed to the soil. This second

curve more closely matches the groundwater monitoring data for day 54. This second model simulation predicted that the groundwater should be remediated to less than 1 ppm VOCs in approximately 28 days, which is less than half of the time predicted for the first fit. This appears to match the day 54 data adequately, which showed that VOCs were below 1 ppm by that time.

Discussion

The two case study applications of the proposed sparging model indicate that it may be a promising method for predicting cleanup time and rate. The model closely matched groundwater monitoring results of Marley et al., 1990, and it predicted cleanup times adequately for both cases.

Many environmental engineering applications of mass transfer, such as air-stripping, are modeled assuming that the aqueous and the air phase are in equilibrium as defined by Henry's Law. Groundwater contaminant concentrations measured during air sparging, and modeling results presented herein, suggest that the residence time of sparging air bubbles in groundwater does not allow equilibration to occur. If equilibration as described by Henry's law occurred, then the expressions $(D/L) \cdot (S/V) \cdot (H/v)$ in equation 14 should be replaced with H/RT^* , where H is Henry's constant, R is the Gas Constant, and T^* is temperature. If Case 1 was modeled using Henry's law, the predicted groundwater BTEX concentration would have been less than 1 ppm in less than a third of a day. As clearly illustrated in Figure 6, the groundwater BTEX level in Case 1 was still around 2 ppm after 13 days of sparging. This indicates that the Henry's Law based model is not a good approximation.

As illustrated in the results of Case 2, model results are sensitive to estimates of the radius of influence of the air sparging bubbles and assumptions of groundwater mixing. In the lower curve, simulation 2B, on Figure 7, it is assumed that there is complete mixing between sparged and unsparged portions of the contaminant plume, and a smaller radius of influence and fraction of groundwater sparged. Under these conditions, there would be a greater number of air bubbles in the volume of influence, and consequently a greater flux of volatile contaminants from the groundwater to the air than. Thus, the predicted cleanup time was reduced by over 50%.

Application of the model is limited to sites that approximate the ideal conditions as described by the simplifying assumptions. Homogeneous and isotropic geological conditions are rare, but surficial deposits of unconsolidated sands and gravel come close to the assumed physical conditions. Moreover, many sites where the model would not provide reasonable results, such as those with high clay content or with clay lenses, are also sites where air sparging may not be feasible. Thus, ideal, simplifying assumptions maybe warranted in many air sparging situations.

Conclusions and Recommendations

Applying the sparging model to two air sparging remediation sites illustrates that a simple computation can be used to estimate groundwater cleanup rates that appear reasonable. The model is promising as a simple

method for preliminary design decisions regarding air sparging.

Model results reflect the accuracy of measurements or estimates of site conditions. It is recommended that model results be compared with groundwater monitoring results from additional sites to further assess its performance. It is also recommended that laboratory-scale testing and field-testing be performed to further identify and quantify the important parameters affecting and controlling air sparging based groundwater remediation.

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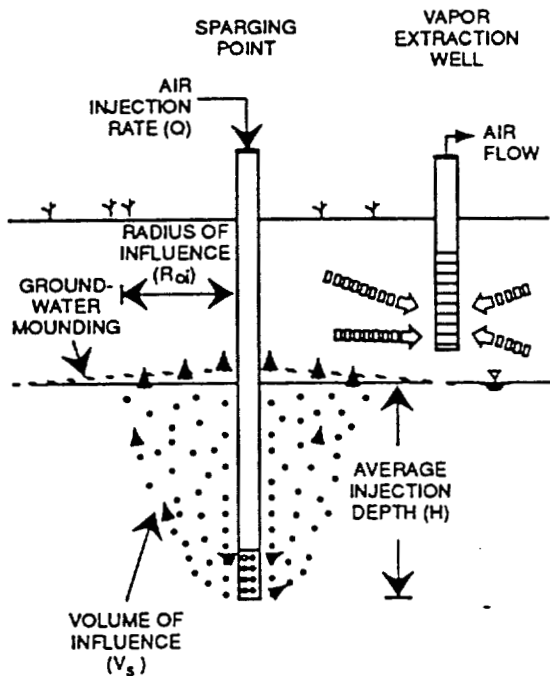


Figure 1.
Schematic Diagram of an Air
Sparging/Vapor Extraction System

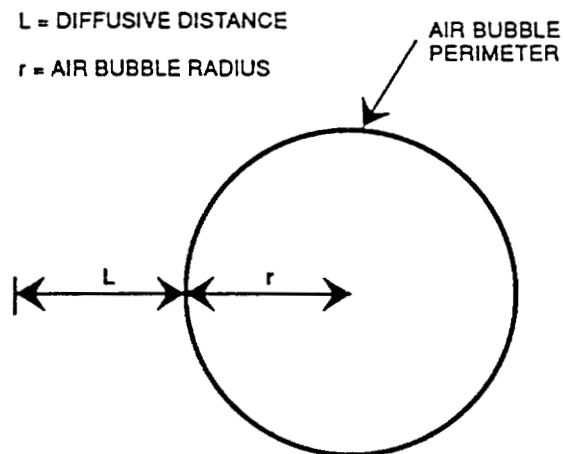


Figure 2.
Idealized Spherical Air Bubbles

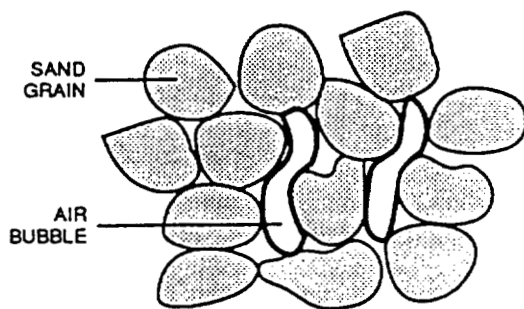


Figure 3.
Possible Geometry of
Actual Air Bubbles

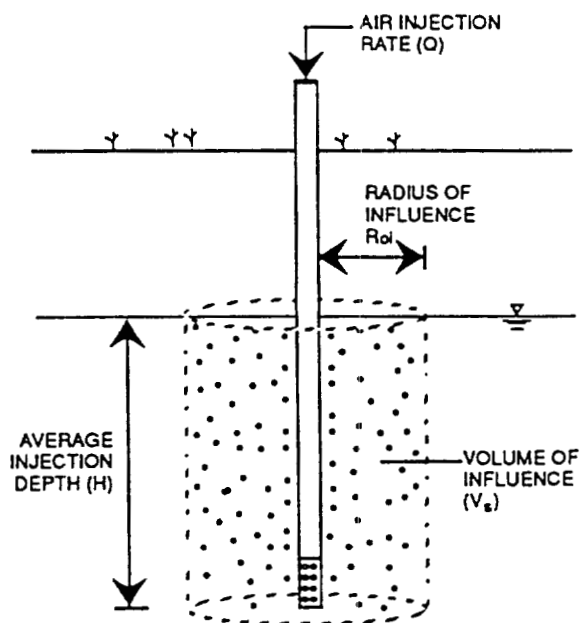


Figure 4.
The Volume of Influence V_s is idealized as
a cylinder around the air injection point
containing randomly dispersed air bubbles.

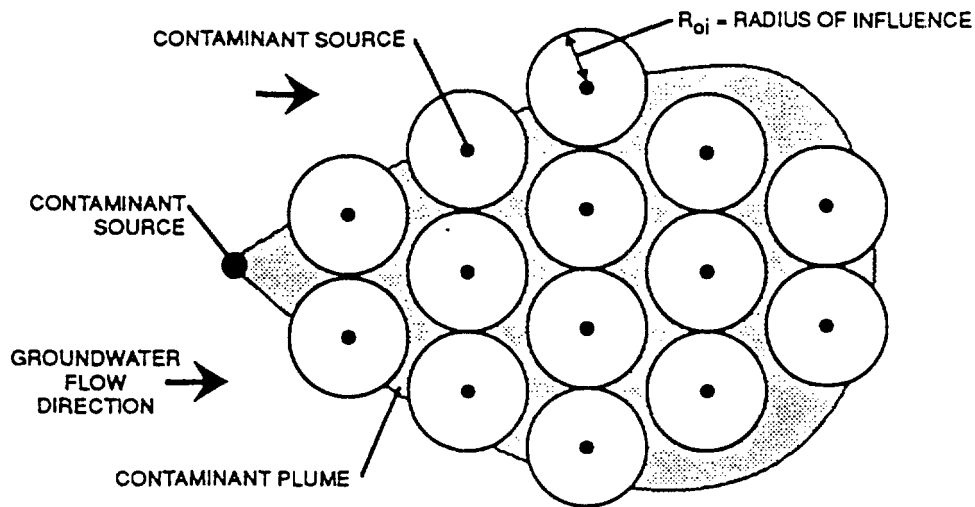


Figure 5. Idealized Grid of Air Injection Points

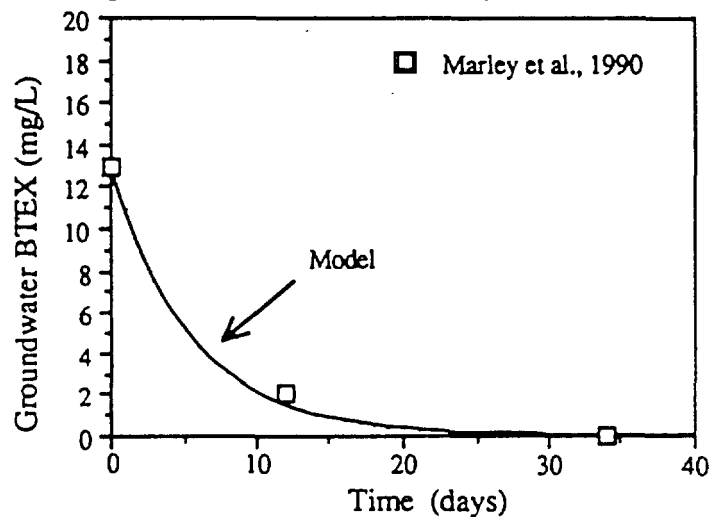


Figure 6. Comparison of Sparging Model with Marley et al., 1991

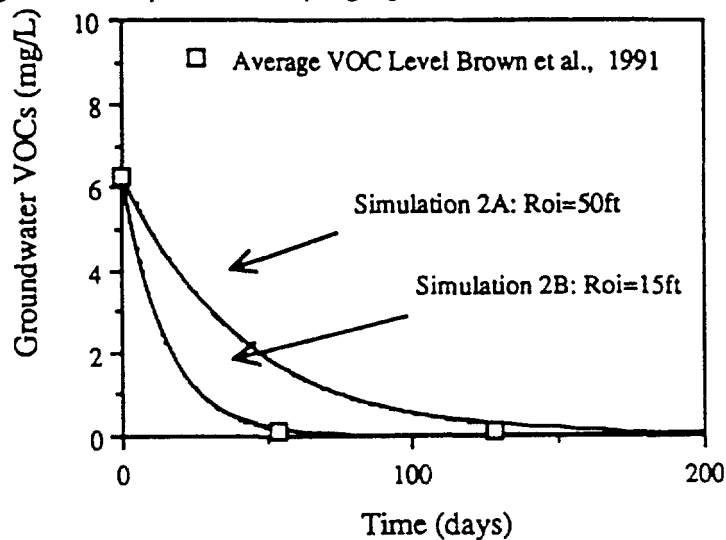


Figure 7. Comparison of Sparging Model with Brown et al., 1991

CALCULATION WORKSHEET

ORIGINATOR R.E. HOEKSTRA DATE 11-1-93 SHEET 1 OF 2
 CALC. NO. AS-1 REV. NO. 0 DATE _____ CHECKED RC 04/20/94
 PROJECT MMR - SUE/AS TASK NO. 9750-K04.03.09
 SUBJECT AIR SPARGING CLEAN-UP RATE

DETERMINE APPROXIMATE AIR-SPARGING CLEAN UP RATE.

PARAMETERS NEEDED.

* D = DIFFUSION COEFFICIENT VARIES FROM 9×10^{-6} TO $1.09 \times 10^{-5} \text{ cm}^2/\text{s}$
 USE $1 \times 10^{-5} \text{ cm}^2/\text{sec}$

* L = DIFFUSION DISTANCE = EFFECTIVE RADIUS OF THE AIR BUBBLES.

* r = EFFECTIVE RADIUS OF AIR BUBBLES. R = OPENING SIZE

$$r = 2 R \left[\frac{6\sigma}{R^2 (\rho_w - \rho_{air}) g} \right]^{\frac{1}{3}}$$

$$= 0.0114 \text{ m}$$

$$= 0.00254 \text{ m}$$

$$r = 2(0.00254 \text{ m}) \left[\frac{6(0.0728 \frac{\text{Kg} \cdot \text{m}}{\text{m} \cdot \text{sec}^2})}{(0.00254)^2 (1000 - 1.29) 9.81} \right]^{\frac{1}{3}}$$

$$r = 4.49 \text{ mm} = 0.00449 \text{ m}$$

$$* \frac{S}{V} = \frac{3}{r} = \frac{667.9}{\text{m}}$$

$$* V = \left[1.04 g r + (1.07 \sigma / r \rho_w) \right]^{\frac{1}{2}}$$

$$V = \left[1.04 \times 9.81 \frac{\text{m}}{\text{sec}^2} \times 0.00449 \text{ m} + \frac{1.07 \times 0.0728 \frac{\text{Kg} \cdot \text{m}}{\text{m} \cdot \text{sec}^2}}{0.00449 \text{ m} \times \frac{1000 \text{ Kg}}{\text{m}^3}} \right]^{\frac{1}{2}}$$

$$V = 0.251 \frac{\text{m}}{\text{sec}}$$



CALCULATION WORKSHEET

ORIGINATOR RE HOOKSTRA DATE 11-1-93 SHEET 2 OF 2
 CALC. NO. AS-1 REV. NO. 0 DATE _____ CHECKED RC 04/20/94
 PROJECT MMR: SVE/AS TASK NO. 9750-K04.03.09
 SUBJECT AIR SPARGING Cleanup RATE

$$V_s = K \cdot TP \cdot R_{oi}^2 \cdot H_n^{-60'} \cdot \frac{1}{L_{75'}^{.35}}$$

$$= TP \cdot 22.9^2 \cdot 18.3 \cdot .35 = 10,540 \text{ m}^3$$

$$Q = 100 \text{ CFM} \times 0.02822 \frac{\text{m}^3}{\text{CF}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{Day}} = 4,063 \text{ m}^3/\text{DAY}$$

$$B = 1.0 (.25) \left(\frac{1.0 \times 10^{-9} \frac{\text{m}^2}{\text{SEC}}}{.000508 \text{ m}} \right) \left(\frac{518.1}{\text{m}} \right) \left(\frac{18.3 \text{ m}}{.25 \frac{\text{m}}{\text{SEC}}} \right) \left(\frac{4,063 \text{ m}^3/\text{DAY}}{10,509 \text{ m}^3} \right)$$

$$B = 0.007216 \text{ DAYS}^{-1}$$

$$C_t = C_0 e^{-Bt}$$

ESTIMATE THE AMOUNT OF CONTAMINATION IN THE GROUND-WATER, THAT WILL BE EFFECTED BY THE AIR SPARGING.

CONC \approx 20 ppm BTEX

Assume $C_0 = 100 \text{ ppm}$ for the total TPH to be Removed.

$$\begin{aligned} \text{VOLUME OF WATER} &= 500,000 \text{ ft}^2 \times 60' \times 0.35 \\ &= 10,500,000 \text{ cu ft.} \times 62.4 \cdot \uparrow \text{ porosity} \\ &= 655,200,000 \text{ lbs} \\ &\times 100 \text{ ppm} \end{aligned}$$

$$\begin{aligned} &= 65,528 \text{ lbs OF CONTAMINATION} \\ &= 29,680 \text{ Kg OF HYDROCARBONS.} \end{aligned}$$



SECTION 8

Pressure Drop Calculations

Velocity Pressure Method
Calculation Sheet

Page 1 of 8

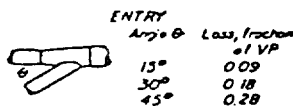
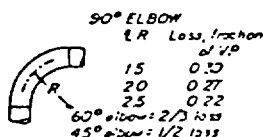
Plant name MMR Elevation _____ Date 10/20/93 Calculated _____ cfm
Location Soil Venting Temperature _____ Refer to drawing _____ (Std conditions) _____ SP"
Department _____ Factor _____ Designer JRM _____ TP"

Checked
RC 06/20/94

Case A Case B Case C

1 Branch or Main duct number		1-A	2-A	4-5 W-5	5-B					
2	Air volume	cfm	150	150	150	150	300			
3	For Slot & Plenum hoods only	Slot area	sq. ft.							
4		Slot velocity	fpm							
5		Slot VP	Fig. 6-16 in. H ₂ O							
6		Slot entry loss factor	Fig. 6-10							
7		Acceleration factor	100VP							
8	Plenum loss factor	Item 6-7								
9	Plenum SP	Item 5X8 in. H ₂ O	3.0	3.0	3.0	3.0				
10	Branch duct dia	inches	4"	4"	4"	4"	4"			
11	Branch duct area	sq. ft.								
12	Branch duct velocity	fpm								
13	Branch duct VP	Fig. 6-16 in. H ₂ O	.184	.184	.184	.184	.737			
14	Straight duct length	ft.	22.0	16.0	25.0	7.0	9.0			
15	Straight duct friction	Fig. 6-17 VP/100	7.4	7.4	7.4	7.4	7.0			
16	Straight duct loss factor	Item 14x15	16.28	11.84	18.5	5.18	6.30			
17	Hood entry loss factor	Section 5 B Fig. 6-10	0.5	0.5	0.5	0.5				
18	Acceleration factor	100VP	1.0	1.0	1.0	1.0				
19	Elbow loss factor No. 2 factor	Fig. 6-12	0.4	0.4	0.4	0.4				
20	Entry loss factor	Fig. 6-13		1.0		1.0	1.0			
21	Special fittings									
22	Duct loss factor	Total of 16 to 21	18.18	13.74	20.40	8.08	7.30			
23	Duct SP loss	Item 13x22 in. H ₂ O	3.35	2.53	3.75	1.49	5.38			
24	Other losses	in. H ₂ O					+ .55			
25	Branch or Main SP loss	Item 9+23x24 in. H ₂ O	6.35	5.53	6.75	4.49	12.68			
26	Governing SP at junction	in. H ₂ O				6.75				
27	Corrected air volume	cfm								
$Q_{corrected} = Q_{duct} \sqrt{\frac{SP_{duct}}{SP_{out}}}$ Fan SP = SP _{out} - SP _{in} - VP _{in}		Hood entry loss factor = 0.5 VP Elbow loss factor = 0.4 VP Branch entry loss factor = 1.0 VP								
28	Hood static pressure "	Items [9+13+(17+18)]								

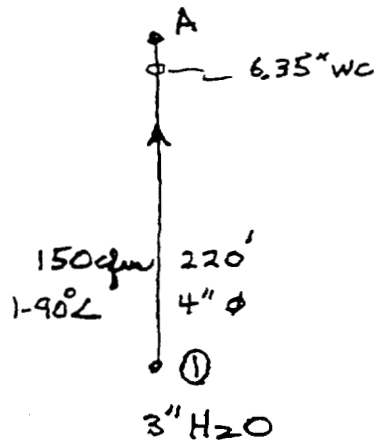
Remarks _____



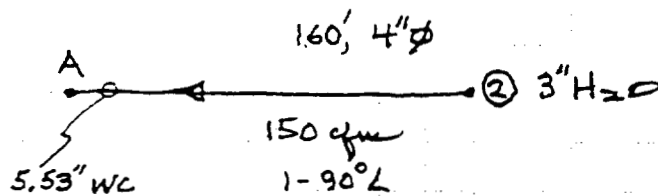
CALCULATION WORKSHEET

ORIGINATOR _____ DATE _____ SHEET 2 OF 8
 CALC. NO. _____ REV. NO. _____ DATE _____ CHECKED RC 04/20/94
 PROJECT MMR TASK NO. _____
 SUBJECT Soil Venting

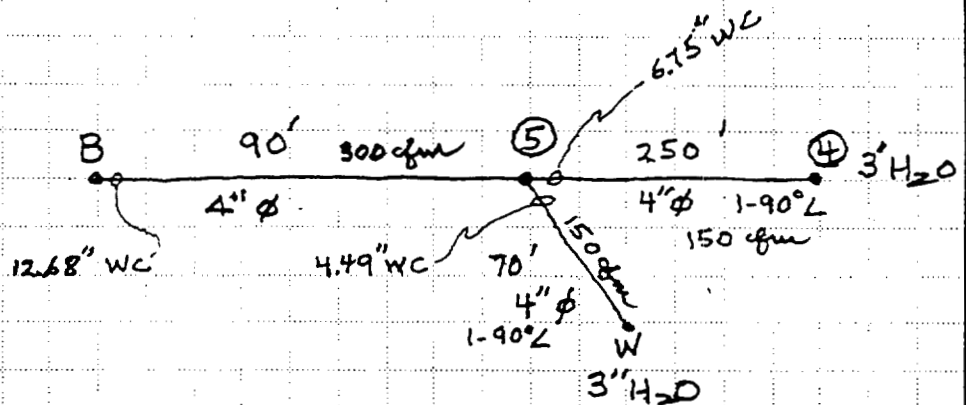
Case A:



Case B:



Case C:



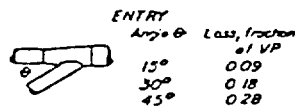
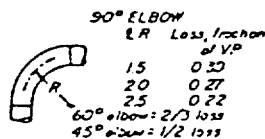
Velocity Pressure Method
Calculation Sheet

Plant name MMR Elevation _____ Date _____ Calculated _____ cfm
 Location Soil Venting Temperature _____ Refer to drawing _____ (Std conditions) _____ SP"
 Department _____ Factor _____ Designer _____ TP"

Checked
RC 04/20/94

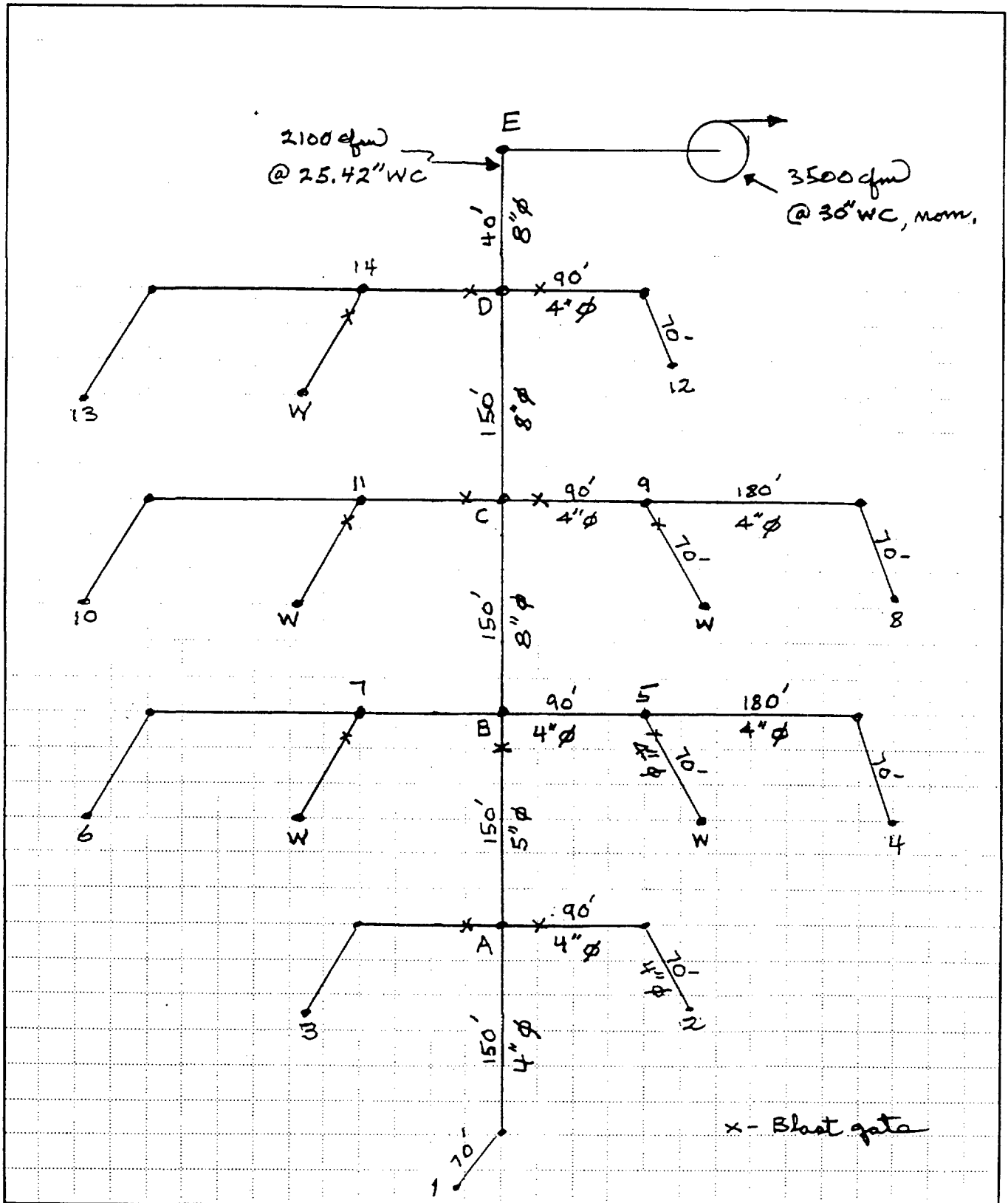
1	Branch or Man duct number		1-A	2-A	A-B	5-B	B-C	C-D	D-E						
2	Air volume	cfm	150	150	450	300	1050	1650	2100						
3	Slot area	sq. ft.													
4	Slot velocity	fpm													
5	Slot VP	Fig. 6-16 in H ₂ O													
6	Slot entry loss factor	Fig. 6-10													
7	Acceleration factor	LOOVP													
8	Plenum loss factor	Item 6-7													
9	Plenum SP	Item 5X8 in H ₂ O	(A)	(B)		(C)									
10	Branch duct dia	inches			5"		8"	8"	8"						
11	Branch duct area	sq. ft.	E	E		E									
12	Branch duct velocity	fpm	N	N	3300	S	3008	4727	6016						
13	Branch duct VP	Fig. 6-15 in H ₂ O	A	A	0.68	A	5.64	1.39	2.256						
14	Straight duct length	ft	(A)	(C)	150	(C)	150	150	40						
15	Straight duct friction	Fig. 6-17 VP/100			5.4		2.95	2.4	2.8						
16	Straight duct loss factor	Item 14x15			8.10		4.43	4.35	1.12						
17	Hood entry loss factor	Section 5 B Fig. 6-10													
18	Acceleration factor	LOOVP													
19	Elbow loss factor No. # factor	Fig. 6-12													
20	Entry loss factor	Fig. 6-13													
21	Special fittings														
22	Duct loss factor	Total of 16 to 21			8.10		4.43	4.35	1.12						
23	Duct SP loss	Item 13+22 in H ₂ O			5.51		2.50	6.05	2.53						
24	Other losses	in H ₂ O			+0.50		-1.5	+7.6	+1.05						
25	Branch or Man SP loss	Item 9+23+24 in H ₂ O	6.35	5.53	12.36	12.68	15.03	21.84	25.42						
26	Governing SP at junction	in H ₂ O		6.35	12.68										
27	Corrected air volume*	cfm													
$* Q_{corr} = Q_{duct} \sqrt{\frac{SP_{out}}{SP_{duct}}}$ $Fan SP = SP_{out} - SP_{in} - VP_{in}$			<p>G G?</p>												
28	Hood static pressure**	Items [9+13+(17+18)]													

Remarks _____



CALCULATION WORKSHEET

ORIGINATOR _____ DATE _____ SHEET 4 OF 8
 CALC. NO. _____ REV. NO. _____ DATE _____ CHECKED RC 04/20/24
 PROJECT MMR TASK NO. _____
 SUBJECT _____

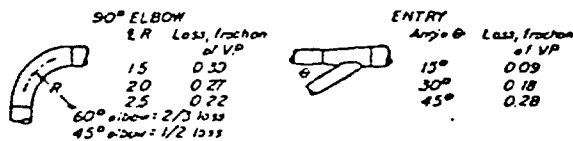


Velocity Pressure Method Calculation Sheet

Plant name MMR Elevation _____ Date _____ Calculated _____ cfm
 Location _____ Temperature _____ Refer to drawing _____ (Std conditions) _____ SP"
 Department _____ Factor _____ Designer _____ TP" RC 04/20/94

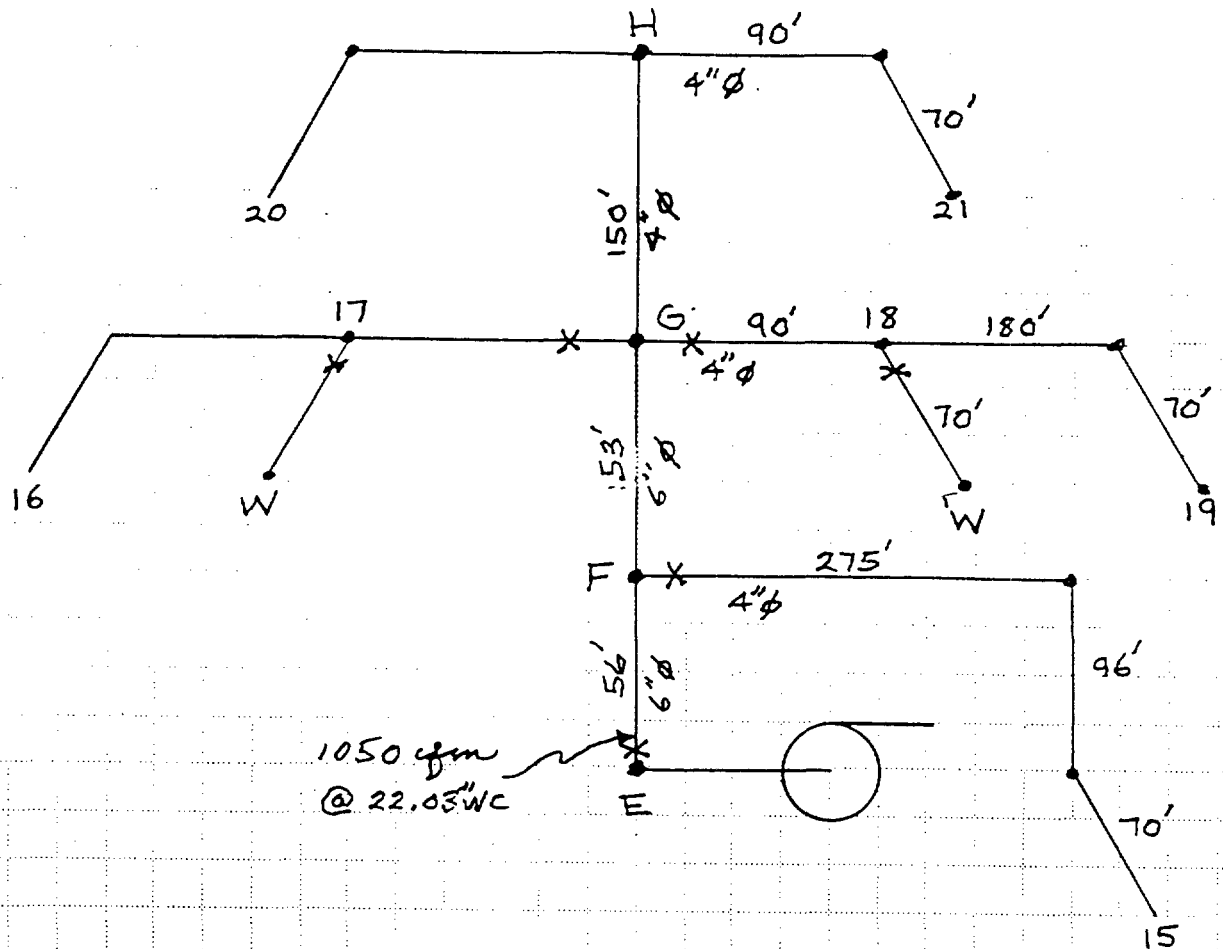
1	Branch or Main duct number		21-H	H-G	18-G	6-F	15-F	F-E						
2	Air volume	cfm		300		900	150	1050						
3	Slot area	sq. ft												
4	Slot velocity	fpm												
5	Slot VP	Fig. 6-16												
6	Slot entry loss factor	Fig. 6-10												
7	Acceleration factor	100VP												
8	Pierum loss factor	Item 6+7												
9	Pierum SP	Item 5XB					3							
10	Branch duct dia	inches		4"		6"	4"	6"						
11	Branch duct area	sq ft												
12	Branch duct velocity	fpm				4584		5348						
13	Branch duct VP	Fig. 6-15				1.31	1.84	1.78						
14	Straight duct length	ft		150		53	44	56						
15	Straight duct friction	Fig. 6-17		7.0		4.2	7.4	4.1						
16	Straight duct loss factor	Item 14+15		10.50		2.23	32.63	2.30						
17	Hood entry loss factor	Section 5 B Fig. 6-10					0.5							
18	Acceleration factor	100VP					1.0							
19	Elbow loss factor No. = factor	Fig. 6-12					0.4							
20	Entry loss factor	Fig. 6-13												
21	Special fittings													
22	Duct loss factor	Total of 16 to 21		10.50		2.23	34.53	2.30						
23	Duct SP loss	Item 13+22		7.74		2.92	6.35	4.09						
24	Other losses			+0.55		+0.57		+0.63						
25	Branch or Main SP loss	Item 9+23+24		5.53	13.82	12.68	17.31	9.35	22.87					
26	Governing SP at junction				13.82		17.31	25.42						
27	Corrected air volume	cfm												
					G	G	G							
$Q_{duct} = Q_{out} \sqrt{\frac{SP_{out}}{SP_{duct}}}$ $Fan SP = SP_{out} - SP_{in} - VP_{in}$														
28	Hood static pressure	Items [9+13+(17+18)]												

Remarks _____



CALCULATION WORKSHEET

ORIGINATOR _____ DATE _____ SHEET 6 OF 8
 CALC. NO. _____ REV. NO. _____ DATE _____ CHECKED RC 04/20/94
 PROJECT MMR TASK NO. _____
 SUBJECT Soil Venting



X = Blast gate



Checked
RC 042094

Pressure Loss in Air Sparging Pipelines
(See schematic, page 8)

Pipe Size		cfm free air	100	200	300	400	500
1	F*		217.4	870	—	—	—
	ΔP**		5.9	—	—	—	—
1½	F		22.3	89.4	—	—	—
	ΔP		0.6	2.4	—	—	—
2	F		6.0	23.9	54.0	94.7	150
	ΔP		0.16	0.6	1.5	2.6	4.1
2½	F		2.3	9.3	20.8	37.1	58.0
	ΔP		—	0.25	0.6	1.0	1.6
3	F		—	—	6.6	11.7	18.3
	ΔP		—	—	0.2	0.3	0.5
3½	F		—	—	—	5.4	8.5
	ΔP		—	—	—	0.15	0.23
4	F		—	—	—	2.7	4.3
	ΔP		—	—	—	—	0.1

Base pipe sizing on ½ to 1 psi/100'

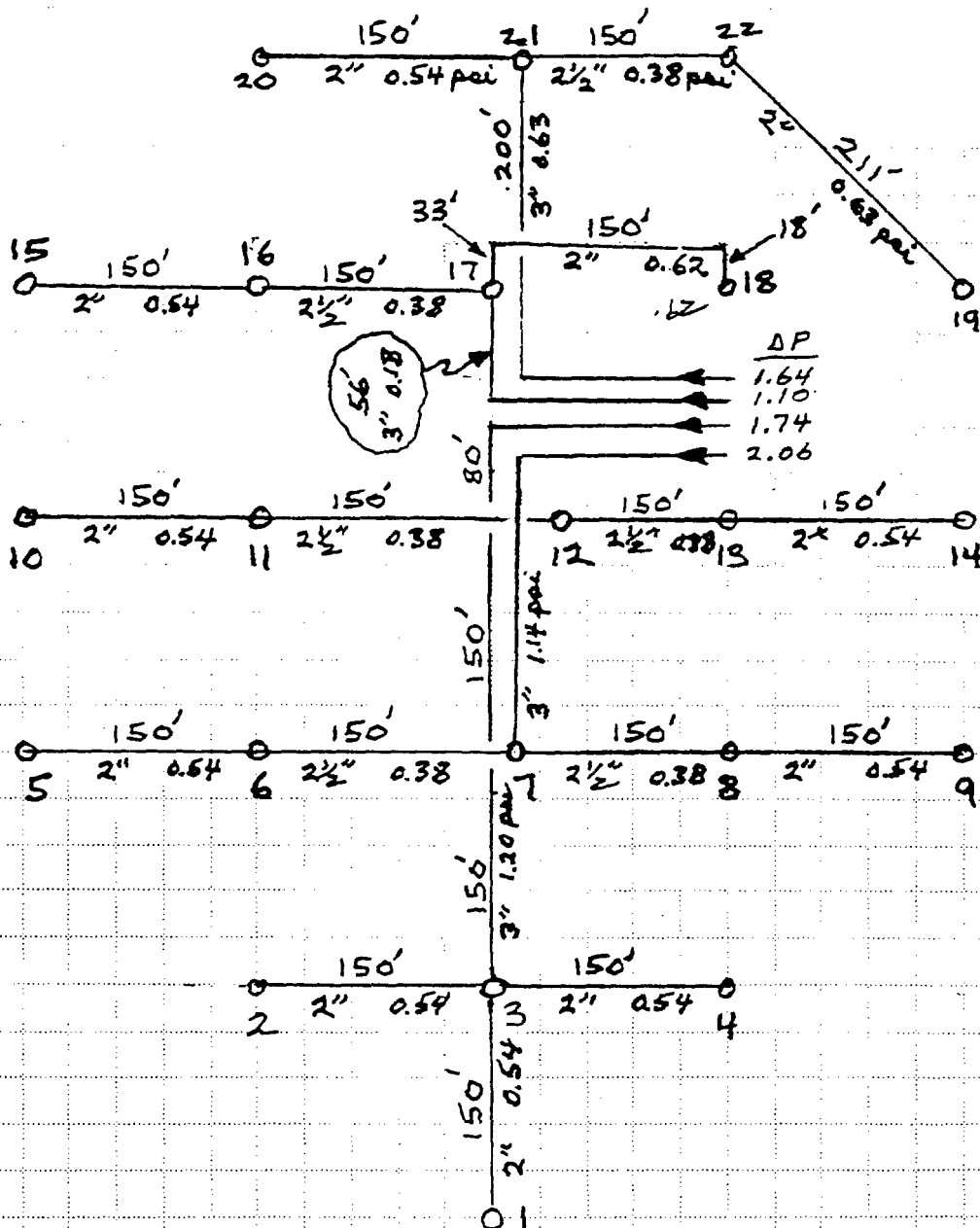
* Factor from Table 1

$$** \Delta P/100' = (100 \times 1.2 \times F \times \frac{14.7}{14.7 + 50}) / 1000 = 0.027 F \text{ psi}/100'$$

CALCULATION WORKSHEET

ORIGINATOR John McDowell DATE _____ SHEET 8 OF 8
 CALC. NO. _____ REV. NO. _____ DATE _____ CHECKED RC 04/20/94
 PROJECT MMR TASK NO. _____
 SUBJECT Pipe sizing for air sparging

Well vertical pipe $\approx 180'$



Fundamentals of Compressed Air Systems

System Standards

Distribution System

Compressor Controls

By R. SCOT FOSS, Manager—Systems Engineering, Sullair Corp., Michigan City, IN

The design of an efficient compressed air system must include pipe size selection and calculations for the total pressure drop between the compressor and the most remote point of air use.

Pipe friction, under dynamic flow conditions, causes a progressive pressure drop in the direction of flow. This pressure drop must be added to the minimum pressure required by the air-powered device for determination of the compressor discharge pressure.

Calculating Pressure Drop—For preliminary calculations, all linear runs of pipe and hose in different sections of the system should be assigned an initial "ball-park" pipe size and reference should be made to Tables I and II. The appropriate volume at inlet conditions (icfm) for that pipe section can then be determined. All

tables are based on volume at system inlet (P_1 as defined in Part I of this article, "System Standards," PE 5/14/81, p 73, file #4020). The calculation determines pressure drop in psi for specific conditions. If the pressure drop is too great, the next larger size of pipe should be used and the calculations repeated. This formula is used with Table I:

$$\Delta P = \frac{L \times A \times F \frac{P_1}{P_2 + P_1}}{1000}$$

where: ΔP = pressure loss, psi

L = pipe length, ft

A = correction factor for valves and fittings (normally 1.2)

TABLE I. FACTORS FOR CALCULATING DIFFERENTIAL PRESSURE FOR ANY SIZE AND LENGTH OF PIPE*

Cu ft free air per min	1/2	3/4	1	1 1/4	1 1/2	1 3/4	2	2 1/2	3	3 1/2	4	4 1/2	5	6	8	10	12
10	50.7	7.8	2.2	0.5													
20	202	30.4	8.7	2.0	0.9												
30	456	70.4	19.6	4.5	2.0	1.1											
40	811	126.3	34.8	8.1	3.8	1.9											
50	—	198	54.4	12.6	5.6	2.9	1.4										
60	—	282	78.3	18.7	8.0	4.2	2.2										
80	—	503	139.2	32.3	14.3	7.5	3.8	1.5									
100	—	785	217.4	50.5	22.3	11.7	6.0	2.3									
120	—	—	318	72.7	32.2	16.8	8.6	3.3									
140	—	—	428	96.9	43.8	22.9	11.7	4.8	1.4								
160	—	—	570	128.3	57.2	29.9	15.3	6.9	1.9								
180	—	—	708	163.3	72.6	37.9	19.4	7.5	2.4								
200	—	—	870	202	89.4	46.7	23.9	9.3	2.9								
240	—	—	—	291	128.7	67.3	34.4	13.4	4.2								
280	—	—	—	395	175	91.6	46.8	18.2	5.7								
320	—	—	—	—	—	—	61.1	23.8	7.5	3.3							
360	—	—	—	—	—	—	77.3	30.1	9.5	4.4	2.2						
400	—	—	—	—	—	—	94.7	37.1	11.7	5.6	2.9						
440	—	—	—	—	—	—	115.5	44.9	14.1	6.6	3.4						
480	—	—	—	—	—	—	137.6	53.4	16.8	7.8	4.0	2.2					
500	—	—	—	—	—	—	150.0	58.0	18.3	8.5	4.3	2.4					
550	—	—	—	—	—	—	181.5	70.2	22.1	10.2	5.2	2.8					
600	—	—	—	—	—	—	215	83.6	26.3	12.7	6.2	3.4					
650	—	—	—	—	—	—	253	98.0	30.9	14.3	7.3	4.0	2.2				
700	—	—	—	—	—	—	294	113.7	35.8	16.6	8.5	4.6	2.6				
800	—	—	—	—	—	—	382	148.4	46.7	21.7	11.1	6.1	3.3				
900	—	—	—	—	—	—	468	188	59.1	27.4	14.0	7.7	4.2				
1,000	—	—	—	—	—	—	600	232	73.0	33.8	17.3	9.5	5.2	2.8			
1,100	—	—	—	—	—	—	723	280.6	88.4	40.9	21.0	11.5	6.2	3.4			
1,200	—	—	—	—	—	—	850	344.0	105.2	48.8	25.0	13.7	7.5	4.0	2.8		

TABLE II. DIFFERENTIAL PRESSURE FOR HOSE

Size of hose, coupled each end, in.	Pressure at line, psig	Free air passing through 50 ft length of hose, cfm											
		20	30	40	50	60	70	80	90	100	110	120	130
		Pressure loss in 50 ft length of hose, psi											
1/2	50	1.8	5.0	10.1	18.1								
	60	1.3	4.0	8.4	14.8	23.4							
	70	1.0	3.4	7.0	12.4	20.0	28.4						
	80	0.9	2.8	6.0	10.8	17.4	25.2	34.6					
	90	0.8	2.4	5.4	9.5	14.8	22.0	30.5	41.0				
	100	0.7	2.3	4.8	8.4	13.3	19.3	27.2	36.6				
	110	0.6	2.0	4.3	7.6	12.0	17.6	24.6	33.3	44.5			
3/4	50	0.4	0.8	1.5	2.4	3.5	4.4	6.5	8.5	11.4	14.2		
	60	0.3	0.6	1.2	1.9	2.8	3.8	5.2	6.8	8.6	11.2		
	70	0.2	0.5	0.9	1.5	2.3	3.2	4.2	5.5	7.0	8.8	11.0	
	80	0.2	0.5	0.8	1.3	1.9	2.8	3.6	4.7	5.8	7.2	8.8	10.6
	90	0.2	0.4	0.7	1.1	1.6	2.3	3.1	4.0	5.0	6.2	7.5	9.0
	100	0.2	0.4	0.6	1.0	1.4	2.0	2.7	3.5	4.4	5.4	6.6	7.9
	110	0.1	0.3	0.5	0.9	1.3	1.8	2.4	3.1	3.9	4.9	5.9	7.1
1	50	0.1	0.2	0.3	0.5	0.8	1.1	1.5	2.0	2.6	3.5	4.8	7.0
	60	1.1	0.2	0.3	0.4	0.6	0.8	1.2	1.5	2.0	2.6	3.3	4.2
	70	—	0.1	0.2	0.4	0.5	0.7	1.0	1.3	1.6	2.0	2.5	3.1
	80	—	0.1	0.2	0.3	0.5	0.7	0.8	1.1	1.4	1.7	2.0	2.4
	90	—	1.1	0.2	0.3	0.4	0.6	0.7	0.9	1.2	1.4	1.7	2.0
	100	—	1.1	0.2	0.2	0.4	0.5	0.6	0.8	1.0	1.2	1.5	1.8
	110	—	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.3	1.5

would be a baghouse, a sandblasting operation, a paint spray application, a very large cylinder, or another application that discharges a large quantity of air to atmosphere in a fraction of a minute regardless of cycles per minute. With such an application, storage is necessary to prevent large system pressure fluctuation, Fig. 1.

In this example, the baghouse uses 20 cu ft in 5 seconds. Conversion to the standard rating gives a flow equivalent of 240 cfm. All volume ratings should be converted to equivalent flows per minute for pipe or receiver sizing calculations, see Table III.

The check valve should be located upstream of the storage vessel to prevent stored air from going to other demands on the system. The pipe upstream of the receiver should be sized to transport 20 cfm to replace air volume that is taken out of the storage vessel during the 5 sec demand. The line downstream of the storage vessel must be sized to handle 20 cu ft in 5 sec, or the equivalent of 240 cfm. If containment-removal equipment is used for this application, it should be placed downstream of the check valve and upstream of the storage vessel. No other users, branches, or drops should be added to this subheader.

With normal selection, the high average demand should be determined on any subheader, branch line, or drop leg at the lower average pressure for the longest run of all sections of that type in the system, Fig. 2. High-single-demand users should not be included in this calculation. Calculations for such high demand users should be evaluated individually.

An examination of the subheader shown in Fig. 2 shows the total demand is 133 icfm at 95 psig, pipe length is 60 ft, and atmospheric pressure is 14.6 psia. The calculation for 1½ in. dia pipe is

$$\Delta P = \frac{60 \times 1.2 \times 37.8 \left(\frac{14.6}{100 + 14.6} \right)}{1000} = 0.36 \text{ psi}$$

This minimal pressure drop indicated that selection of 1½ in. subheader piping is satisfactory.

Heaviest usage for branch lines is 40 icfm at 95 psig, length is 40 ft, and atmospheric pressure is 14.6 psia. Calculation for 1 in. pipe gives a 0.22 psi pressure loss. Although 1 in. pipe is the indicated selection, ¾ in. would also be acceptable with only 0.8 psi pressure loss. But because the difference in installed cost between ¾ and 1 in. pipe is so insignificant, the selection of 1 in. is better in terms of flexibility, storage, and growth.

Drop Legs—The same calculations used for subheaders and branches are also used when determining drop leg size. It is advisable to select the same size respectively for all subheaders, for all branches, and for all drop legs. In the example just calculated, all subheaders would be 1½ in. pipe, and all branch lines 1 in. This procedure reduces cost and allows for movement of equipment and future expansion of the total system. Because the high average demand was used, sections with lower demand will have lower pressure drops and help provide storage for other demands on the system. (This factor does not apply to the high-single-demand users.)

Sizing the Header—The header section has two essential functions: transport and storage. (Without storage, the system cannot be free of pressure fluctuation.)

Selection of pipe size is only one consideration in header design. Geometry, balance, entry, flexibility, valving, location of the header relative to the distribution of drop legs (P_d), and growth of the system must also be considered.

The header should be sized for no more than 1 psi pressure loss at anticipated maximum demand at least 2 years from startup of the system. It is even better to plan header size and design for anticipated demand 5 years from startup. Oversizing the header is the best investment that can be made in the total system.

TABLE III. COMPRESSED AIR RECEIVER CAPACITY, CU FT

Tank dimensions, in.	Capacity, gal	Pressure, psig						
		0	50	100	125	150	175	200
14 x 36	20	2.7	12.0	20.8	25.3	30.0	34.4	38.9
16 x 36	30	4.0	18.0	31.2	38.0	45.0	51.6	58.4
20 x 48	60	8.0	36.0	62.4	76.0	90.0	103.2	116.8
20 x 63	80	10.7	48.0	83.2	101.3	120.0	137.6	155.7
24 x 68	120	16.0	72.0	124.8	152.0	180.0	206.4	233.6
30 x 84	240	32.0	144.0	249.6	304.0	360.0	412.8	467.2

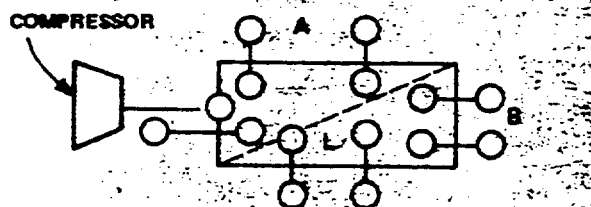


Fig. 3. Loop-type header shown here is a good arrangement for a plant air distribution system when a single compressor is used.

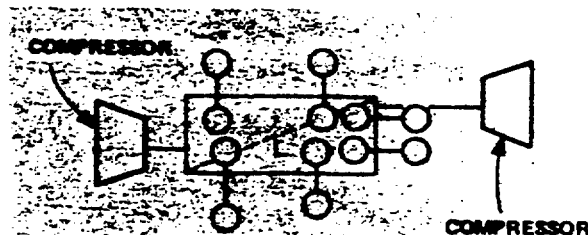


Fig. 4. Unit-loop system may be used when an existing header is too small or when space is not available for adding a compressor at the original location.

Fig. 5. Grid-type header is commonly used but is less desirable than loop-type distribution system.

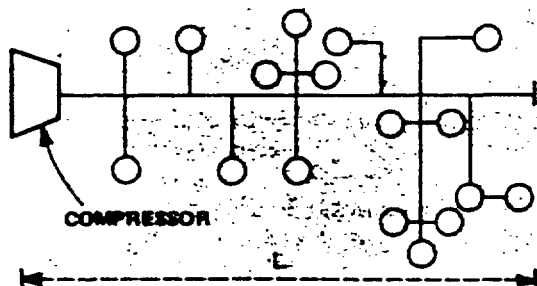
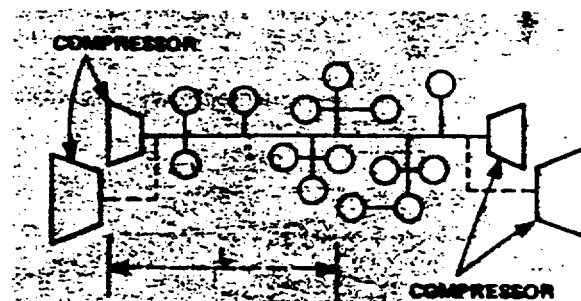


Fig. 6. Unit-grid header system provides ideal air distribution when multiple compressors are used.



To calculate higher demand, the plant engineer should estimate not only increases in equipment, but also increases in production as a percentage of what the initial demand will be. Each increase in production with the same equipment nets a proportionate increase in demand for air volume. For example:

Current demand at riser (P_r), cfm	1080.0
20 percent increase over initial planned rate of production (0.20×1080), cfm	216.0
New equipment added over 2 years	
Four $2\frac{1}{2}$ hp grinders, 70 cfm at 50 percent use factor* per min:	140.0
Eight blowguns, 18 cfm at 10 percent use factor	14.4
Five chippers, 20 cfm at 40 percent use factor	40.0
One baghouse, 52 cfm, at 100 percent use factor	52.0
Total new equipment, cfm	264.4
Total air demand 2 years from startup, cfm	1542.4

*Use factor = maximum percentage of use for any given minute to determine actual flow rate.

In calculating actual air use, the rated air requirement of an air-operated device is multiplied by the percentage of time in any minute it may operate. This value cannot be treated as an average. The number of times it operates in the week or day is unimportant. Note: the 2 year method applies only to header and riser sizing.

The next step is to determine the type of header and the method of determining length for sizing calculations. Header types are loop, unit loop, grid, and unit grid, as shown in Fig. 3, 4, 5, and 6. Figures 3 and 5 show the better designs, but when an existing header is too small, or when there is no room to add a compressor at the original location, the arrangements in Fig. 4 and 6 may also be applied.

Plant engineers should be aware that these systems are undesirable from an energy cost point of view, because when pressure for the compressors is sensed at multiple locations there is always more compressor capacity on line than necessary when the system is at part load.

After the pipe length to be used in the calculation is determined, the previously given formula can be used.

Riser Sizing—The riser is the pipe between the last

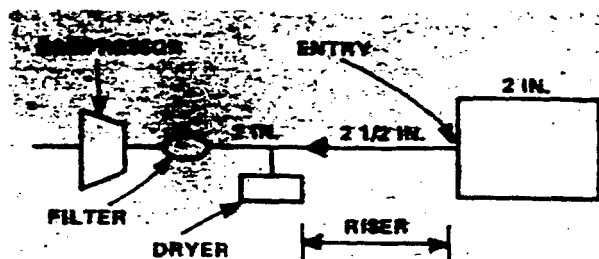


Fig. 7. Increasing the riser size allows contaminant dropout in the drop leg.

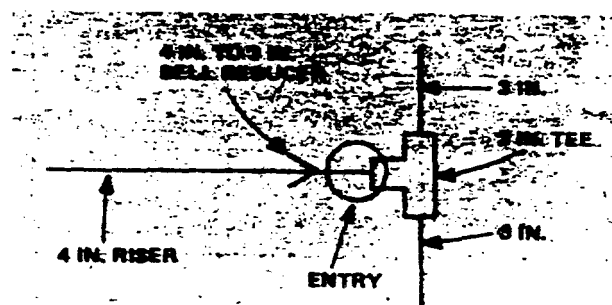


Fig. 8. This 4 in. riser entering a 3 in. tee is a poor selection and will result in a significant pressure drop.

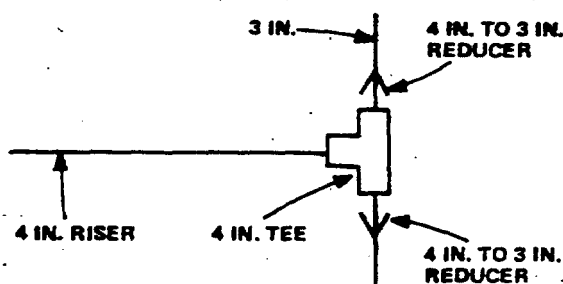


Fig. 9. Using a 4 in. tee with reducers after the tee increases entry and system capacity of example in Fig. 8 by 25 percent.

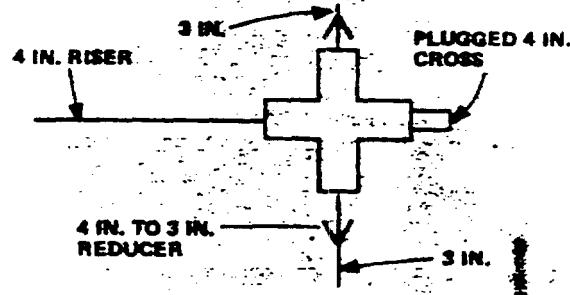
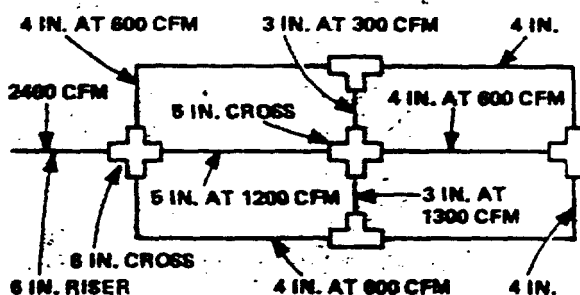


Fig. 10. When system growth is likely, the entry should be to a plugged cross.

Fig. 11. The addition of crossover connections allows for growth in the distribution system.



piece of compressor equipment, including dryers, filters, and other auxiliary equipment, and the entry point in the overhead piping where header distribution begins. The riser includes horizontal as well as vertical runs between these points.

The riser must transport air to the header and furnish the pressure signal from the header through accessories to the compressor. The riser also reduces the velocity of compressed air to minimize the amount of contaminants carried to the header. Therefore, a drop leg should be used in the riser. It is desirable to pitch the overhead horizontal runs of the riser away from the header toward the drop leg and enter the header from the side or bottom.

The riser should be the next nonnominal pipe size larger than the header or the interconnect piping on the compressed air equipment, whichever is larger, to facilitate

contaminant drop out in the drop leg, Fig. 7.

The place where the riser connects to the header is the entry, a very important design point in the system. The best of intentions are frequently destroyed by a poorly selected entry, Fig. 8.

In the example in Fig. 8, the entry is 3 in. pipe. Using a 4 in. tee, with reducers after the tee, as in Fig. 9, increases entry—and system—capacity by 25 percent.

When system growth is planned, the entry should be designed according to the arrangement in Fig. 10.

Doubling the growth of this system is a simple matter of sizing the riser and entry for 6 in. pipe and the crossover for 5 in. pipe with a 4 in. mating tee at the far end of the crossover. The system also requires 4 in. tees centered on the north and south sides of the header. As the distribution grows, the system should eventually appear as shown in Fig. 11; crossover connections are being added progressively.

This layout makes it possible to install the system at the lowest initial cost for 1200 cfm and gradually add twice as much air with a minimum investment at each point of growth, while maintaining balance and storage during growth. The alternative is to install a 6 in. header system to start with, doubling the initial expense.

This article on pipe selection and pressure drop calculations is the second in a series covering three broad subject areas that are important to compressed air system design and operation. The first article (PE 5/14/81, p 73, file #4020) discussed system standards. The third and final article will review compressor controls.

For complimentary copy of this article circle 265 on post card

SECTION 9

Treatment Technology Selection

EMISSION CONTROL ALTERNATIVES FOR THE MMR SOIL VAPOR EXTRACTION AIR SPARGING SYSTEM

The most frequently used approach to control a point source emission like a soil vapor extraction system is the application of add-on control devices. The two most common control alternatives for the vapor stream from a SVE system are:

- adsorption on granular activated carbon
- catalytic oxidation

Granular Activated Carbon(GAC)

Activated carbon is a common method of vapor phase treatment. The use of GAC is popular for the following reasons:

- relative ease of implementation and operation
- its ability to be regenerated for repeated use
- its applicability to a wide range of contaminants and flow rates.
- many vendors have skid-mounted prefabricated units available.

GAC is economical only for relatively low mass removal rates. When the vapor concentration is high, carbon replacement or regeneration rates are generally prohibitively expensive.

A GAC system properly sized and operated will be able to operate at efficiencies of 95 to 99% . This will meet the MASSDEP requirements of 95% removal efficiency.

The effectiveness of a carbon system will be reduced if the relative humidity of the air stream is above 50% or if the temperature of the air stream is above 80 degrees. Therefore the air stream needs to be cooled and the relative humidity of the air stream will need to be reduced.

The major disadvantage of a GAC system is the disposal of the used carbon or the disposal of the liquid waste generated from the regeneration of the carbon if a regenerative system is used.

For a standard carbon treatment system where the used carbon is taken off site for regeneration or disposal, the carbon will cost about \$2.00 a pound. Each pound of carbon will adsorb approximately 0.15 pounds of hydrocarbon vapors. The estimated spill is 70,000 gallons of jet fuel. If 75% of the jet fuel is captured by the venting system the total weight of the removed fuel will be 341,250 pounds at a cost of \$4.55 million.

If an on-site carbon regeneration system is used the equipment costs will be approximately \$210,000 and the system will have monthly energy and disposal costs of approximately \$9,000.

Catalytic Oxidation

Catalytic oxidation units are used to control a wide variety of continuous emission streams containing VOCs. These units are typically applied to emission streams that are dilute mixtures of VOCs and air. In this process, the vapor stream is heated and passed through a combustion unit in contact with a catalyst. The catalyst unit is generally a metallic mesh, ceramic honeycomb or packed bed consisting of catalyst impregnated pellets. The catalyst is typically composed of a precious metal formulation (e.g. palladium or platinum) that facilitates the transformation of the contaminant molecules into carbon dioxide and water.

In the catalytic oxidation process, the catalyst accelerates the chemical reaction without undergoing a chemical change itself. The catalyst adsorbs the contaminant molecules on itself and this higher concentration of reactive materials serves to increase the reaction rate and facilitate the oxidation process. In order to keep the catalyst from overheating, the emission stream must be carefully monitored and the inlet concentrations must be diluted to be kept below 25% of the LEL. This is accomplished by diluting the incoming air stream.

The main advantage of the catalytic oxidation unit over other types of thermal incineration units is the much lower temperature that the catalytic oxidation unit can operate at. These systems operate at 600 to 900 degrees F, where as a thermal incineration unit would operate at temperatures of 1400 degrees F or higher. This lower temperature results in much lower fuel costs. Natural gas or propane are typical fuels used as supplemental fuel when the vapor stream does not contain sufficient heat values for a self-sustaining reaction. Energy costs can also be reduced by reclaiming heat from the exhaust gases, using the exhaust to preheat the incoming influent vapor stream.

Catalysts can be "poisoned" by the addition of trace amounts of heavy metals. Also halogens in the emission stream can severely affect the catalyst's performance. The JP-4 vapors to be destroyed by the catalytic oxidization unit do not contain any of the materials that could "poison" the catalyst, therefore this will not be a potential problem at the MMR site.

Catalysts do lose their effectiveness with time and the life of the catalyst in a catalytic oxidation unit is estimated to be from two to five years. The unit would be able to be used for the entire time of the remediation at MMR without the expense of replacing the catalyst.

Destruction efficiencies of 95% can be easily achieved with catalytic oxidation. Higher efficiencies (98 to 99 %) are possible but require larger catalyst volumes and are more expensive.

Catalytic oxidization units have been applied to continuous emission streams with flow rates up to 50,000 scfm and numerous units have been installed to treat the emissions from soil vapor extraction systems.

If an catalytic oxidization unit is used the equipment costs will be approximately \$153,000 and the system will have an monthly energy costs of \$8500.

SELECTION PROCESS

During the initial design of the system, only two options were seriously considered, carbon adsorption with off-site disposal and catalytic oxidation. The costs of carbon adsorption with off site disposal were prohibitive for this site and catalytic oxidization was the selected technology. The selection of this technology was based on the following:

- Catalytic oxidation is a proven technology that has been used on several soil vapor extraction projects.
- Catalytic oxidation can easily achieve the 95% reduction required by MASSDEP and has been approved by MASSDEP for use at other sites on the Cape.
- Catalytic is cost effective and will destroy the contaminants rather than collect them for future handling and disposal.

In order to make a reasonable comparison costs data was gathered from vendors of Regenerative carbon systems. After an extensive search, only two vendors were found that provide this type of systems. One of these vendors was able to provide a detailed cost estimate for a 3500 SCFM system with all the necessary equipment. Using these costs and considering the costs associated with the disposal of the collected contaminants, the catalytic oxidation unit is still the most cost effective method of disposing of these contaminants.

EDB

Some concern exists over the possibility that the air sparging system could strip EDB from the groundwater and thus be captured by the soil vapor extraction system and then routed through the catalytic oxidation unit. A very conservative estimate was made and the maximum EDB concentration that could be in the soil gas was estimated at 0.000396 ppm. The Manufacturer of the catalytic oxidation unit (Global Technologies) was contacted and Mike Disapato stated that as long as the concentrations of EBD stayed below 5 ppm in the soil vapor that there would be no problems with the operation of the catalytic oxidation unit. The supporting Calculations are attached.

Additional information on the EDB and the catalytic oxidation unit.

Per conversation with Chris Anguil of Global Technologies on april 4, 1994 the concentrations of EDB in the soil gas will be totally destroyed as they are routed through the catalytic oxidation unit. The byproduct of the destruction will be hydrogen bromide which has a much lower risk than EDB. The attached calculations conservatively assume that the EDB will be pass through the catalytic oxidation unit without any destruction.

CALCULATION WORKSHEET

ORIGINATOR R.E. HOEKSTRA DATE 2/28/94 SHEET 1 OF 4
CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED RC 04/20/94
PROJECT MMR - SVE/AS TASK NO. 9750-K04.03.09
SUBJECT EDB CONC. to CATALYTIC OXIDATION UNIT.

Purpose: To Determine a Maximum possible CONCENTRATION OF EDB THAT COULD REACH THE CATALYTIC OXIDATION UNIT.

Calculation Approach.

THE APPROACH USED TO OBTAIN THIS ESTIMATE IS AS FOLLOWS:

- 1) DETERMINE HENRY'S LAW CONSTANT FOR EDB

$$H_m = 6.67 \text{ E-04 ATM} \cdot \text{m}^3/\text{mol}$$

THIS VALUE IS FROM THE "MMR RISK ASSESSMENT HANDBOOK"

- 2) DETERMINE MAXIMUM CONCENTRATION OF EDB IN GROUNDWATER AT THE REMEDIAL SITE

$$\text{MAX CONC} = 1.06 \text{ ppb}$$

RZ
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5-17-94

- 3) THE EDB IN THE GROUNDWATER WILL BE STRIPPED BY THE AIR SPARGING AT THE RATE OF

$$C_t = C(0) e^{-Bt}$$

where C_t = CONC. @ time t
 $C(0)$ = INITIAL CONCENTRATION



CALCULATION WORKSHEET

ORIGINATOR R.E. HOEKSTRA DATE 3/1/94 SHEET 2 OF 4
 CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED RC 04/20/94
 PROJECT MMR - SVE / AS TASK NO. 9750 - K04.03.09
 SUBJECT EDB CONC. TO CATALYTIC OXIDATION UNIT

$$B = H_u \times \frac{Q}{V_s}$$

\swarrow Air injection rate
 \nwarrow Volume of groundwater treated by one sparging well.

4) CONVERT H_m to " H_u " THE UNITLESS HENRY'S CONSTANT *

$$H_u = 6.67 E-04 (55,600) (7.49 \times 10^{-4})$$

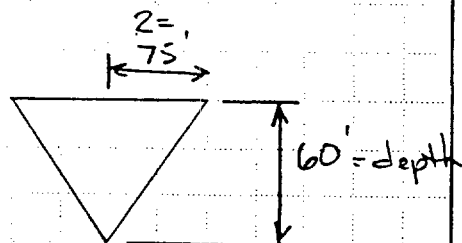
$$H_u = 2.78 \times 10^{-2}$$

* REFERENCE: AMERICAN WATER WORKS ASSOCIATION, WATER QUALITY & TREATMENT PP 234-241

5) $Q = 100$ SCFM

$$V_s = \frac{1}{3} \pi (75)^2 \times 60$$

$$V_s = 353,429$$



MULTIPLY BY POROSITY TO GET ACTUAL VOLUME OF WATER $\eta = 0.30$

$$V_s = 106,029 \text{ cu. feet.}$$

$$6) B = 2.78 \times 10^{-2} \times \frac{100 \text{ SCFM}}{106,029 \text{ cu. ft.}}$$

$$\therefore B = 2.622 \times 10^{-5} \text{ min}^{-1}$$



CALCULATION WORKSHEET

ORIGINATOR RETROEKSTRA DATE 3/30/94 SHEET 3 OF 4
 CALC. NO. _____ REV. NO. 1 DATE _____ CHECKED RC 04/20/94
 PROJECT MMR TASK NO. 9750-K04.03.09
 SUBJECT EDB CONC to CADOX UNIT

7.) DETERMINE REDUCTION IN EDB CONCENTRATION IN THE GROUNDWATER TO DETERMINE REMOVAL RATE

$$CT = C_0 * e^{-2.622 * 10^{-5} \text{ min}^{-1} * t}$$

$$CT = C_0 * e^{-0.0378 \text{ DAYS}^{-1} * t}$$

Using this equation all the EDB will be removed in 4 months. see graph.

* For the Risk calculation, The Daily Reduction will be Averaged for the first month & the duration of the EDB Emissions will be 4 months.

SEE ATTACHED TABLE FOR CALCULATIONS.

$$\Delta C = 1.06 (0.0009236)$$

$$\Delta C = 0.000979 \text{ ug/L} \cdot \text{hr} = \text{TOTAL EDB Removed by one well in one hour.}$$

$$\text{Total} = 0.000979 * 106,029 \text{ w.ft.} * 28.32 \text{ L/w.ft.}$$

$$\text{Total} = 2,939 \text{ ug/Hour per A.S. well.}$$

8.) DETERMINE CONC. IN SOIL GAS TO CADOX UNIT

$$\text{CONC} = \frac{2,939 \text{ ug/hour}}{169,920 \text{ L/hour} \uparrow \text{one well}} * \frac{600}{3500} = 0.003 \text{ ug/L} = 3.04 \text{ ug/m}^3$$

↑ dilution due to ratio of SOIL VENTING to AIR SPARGING



CALCULATION WORKSHEET

ORIGINATOR RE. HOEKSTRA DATE 3/1/94 SHEET 4 OF 4
 CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED RC 04/20/94
 PROJECT MMR SUE/AS TASK NO. 9750-K09.03.09
 SUBJECT EDB CONC. TO CATALYTIC OXIDATION UNIT

9) CONVERT $\mu\text{g}/\text{m}^3$ to ppm EDB MW = 188

$$\text{ppm} = \frac{\mu\text{g}/\text{m}^3 (24.5)}{\text{MW} (10^3)}$$

$$\text{ppm} = \frac{3.04 \mu\text{g}/\text{m}^3 \times 24.5}{188 \times 10^3} =$$

$$3.96 \times 10^{-4} \text{ ppm}$$

EDB in Air
SPARGING GASES

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CONCLUSIONS.

EVEN DOING A VERY CONSERVATIVE CALCULATION ON THE REMOVAL RATES OF EDB FROM THE

GROUNDWATER, THE MAXIMUM CALCULATED

CONCENTRATION OF EDB IS $3.96 \times 10^{-4} \text{ ppm}$

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3-29-94

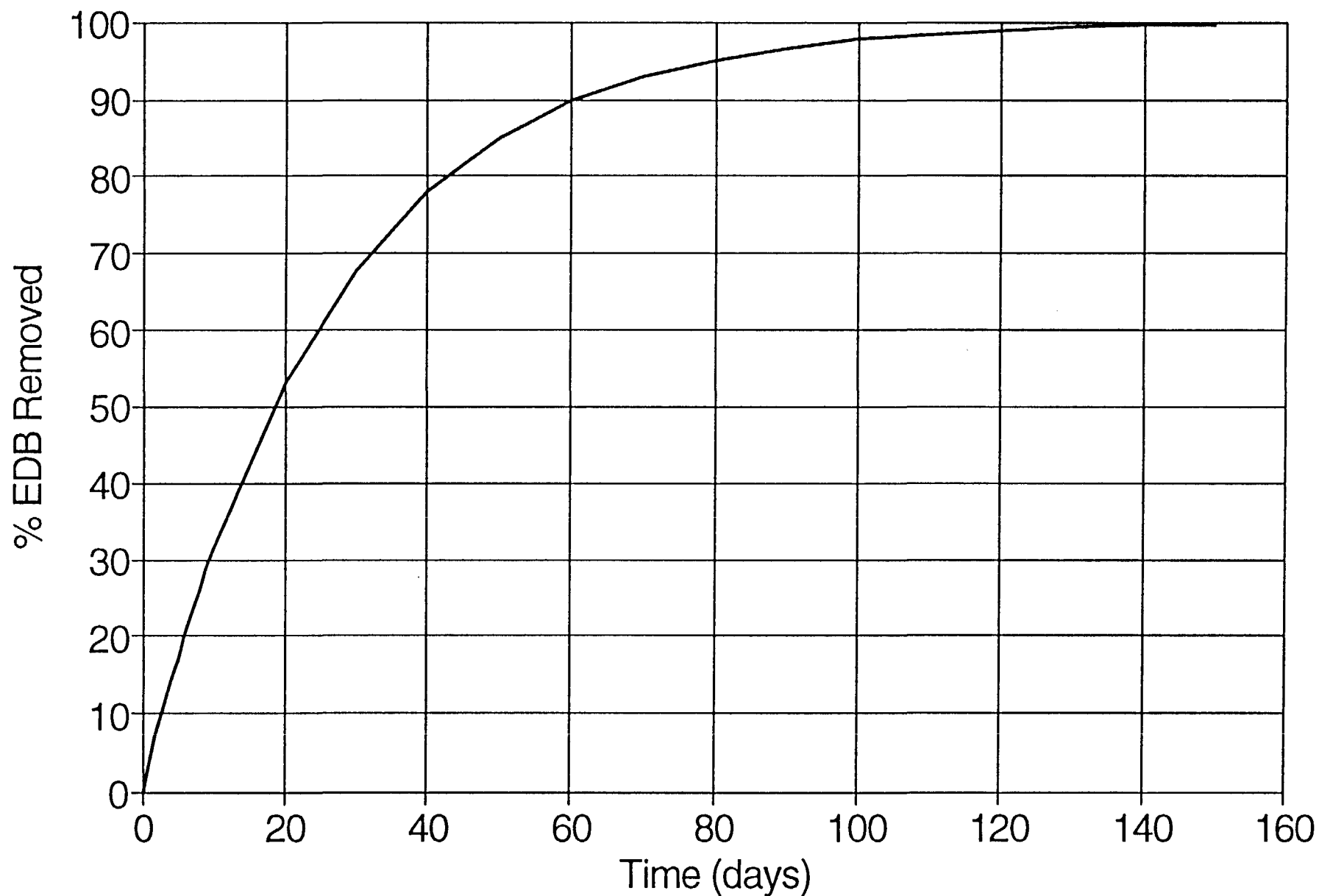
IN THE AIR SPARGING GASES. MIKE DISAPATO OF GLOBAL TECHNOLOGIES STATED THAT CONC. UP TO 5ppm WOULD NOT EFFECT THE CATALYTIC OXIDATION UNIT.



EDB Removal by Day

Day	%remove	Day+1hr.	%remove	%differen
1	3.70945	1.041667	3.860988	0.151538
2	7.281299	2.041667	7.427216	0.145917
3	10.72065	3.041667	10.86116	0.140504
4	14.03243	4.041667	14.16772	0.135292
5	17.22135	5.041667	17.35162	0.130274
6	20.29198	6.041667	20.41742	0.125441
7	23.24871	7.041667	23.3695	0.120788
8	26.09576	8.041667	26.21207	0.116308
9	28.8372	9.041667	28.94919	0.111993
10	31.47695	10.04167	31.58479	0.107839
11	34.01878	11.04167	34.12262	0.103839
12	36.46632	12.04167	36.56631	0.099987
13	38.82307	13.04167	38.91935	0.096278
14	41.0924	14.04167	41.1851	0.092706
15	43.27754	15.04167	43.36681	0.089268
16	45.38163	16.04167	45.46759	0.085956
17	47.40768	17.04167	47.49044	0.082768
18	49.35856	18.04167	49.43826	0.079697
19	51.23708	19.04167	51.31382	0.076741
20	53.04592	20.04167	53.11981	0.073894
21	54.78765	21.04167	54.85881	0.071153
22	56.46478	22.04167	56.5333	0.068514
23	58.0797	23.04167	58.14567	0.065973
24	59.63471	24.04167	59.69824	0.063525
25	61.13204	25.04167	61.19321	0.061169
26	62.57383	26.04167	62.63273	0.0589
27	63.96214	27.04167	64.01885	0.056715
28	65.29894	28.04167	65.35355	0.054611
29	66.58616	29.04167	66.63875	0.052585
30	67.82563	30.04167	67.87626	0.050635
Average				0.09236

EDB Removal From Air Sparging Vs. Time



CALCULATION WORKSHEET

ORIGINATOR Rebecca Stra DATE 3/29/94 SHEET 1 OF 2
CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED K.C. 04/20/94
PROJECT MMR / SVE/AS TASK NO. 9750-K04.03.09
SUBJECT EDB Air Modeling & Risk Assessment.

Purpose: To Determine the maximum possible
Ground level air concentration & the
Risk associated with that conc.

EPA's SCREEN MODEL WILL BE USED FOR THE AIR
EMISSIONS MODELING

Screen Input

Source type - Point

Emission Rate g/s

$$= 2,939 \text{ ug/hr-well} * 6 \text{ wells} * \frac{600}{3500} * \frac{1}{3600} =$$

$$= 0.836 \times 10^{-6} \text{ g/sec}$$

Stack Height - 25' = 7.62 METERS

Stack Diameter = 14" = 0.36 m

$$\begin{aligned} \text{Stack Gas Velocity} &= \frac{3500 \text{ CFM}}{1.07} \times \frac{1 \text{ min}}{60 \text{ sec}} = 54.5 \text{ ft/sec} \\ &= 16.63 \text{ m/sec} \end{aligned}$$

Stack Temp = 450 °K

Air Temp = 293 °K



CALCULATION WORKSHEET

ORIGINATOR RE HOEKSTRA DATE 3/29/94 SHEET 2 OF 2
CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED RC 04/20/94
PROJECT MMR - SVE/AS TASK NO. 9750-K04.03.09
SUBJECT EDB AIR MODELING & Risk Assessment.

RECEPTOR HT = 2.0 m

RUN OPTION

FULL METEOROLOGY

SEE ATTACHED Screen Computer Run.

MAX CONC = $1.165 \times 10^{-4} \text{ ug/m}^3$
OF EDB
AT
Receptor
LOCATION

$$= 1.165 \times 10^{-7} \text{ mg/m}^3$$



1

03-30-94

16:44:34

*** SCREEN-1.1 MODEL RUN ***

*** VERSION DATED 88300 ***

Edb Modeling for VES/AS system at MMR

SIMPLE TERRAIN INPUTS:

SOURCE TYPE = POINT
 EMISSION RATE (G/S) = .8360E-06
 STACK HEIGHT (M) = 7.62
 STK INSIDE DIAM (M) = .36
 STK EXIT VELOCITY (M/S) = 16.60
 STK GAS EXIT TEMP (K) = 450.00
 AMBIENT AIR TEMP (K) = 293.00
 RECEPTOR HEIGHT (M) = 2.00
 IOPT (1=URB,2=RUR) = 2
 BUILDING HEIGHT (M) = .00
 MIN HORIZ BLDG DIM (M) = .00
 MAX HORIZ BLDG DIM (M) = .00

BUOY. FLUX = 1.84 M**4/S**3; MOM. FLUX = 5.81 M**4/S**2.

*** FULL METEOROLOGY ***

*** SCREEN AUTOMATED DISTANCES ***

*** TERRAIN HEIGHT OF 0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES

DIST (M)	CONC (UG/M**3)	U10M STAB	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
100.	.1077E-03	2	4.0	4.0	1280.0	16.1	19.4	10.9 NO
200.	.1099E-03	3	3.0	3.0	960.0	18.9	23.8	14.4 NO
300.	.1023E-03	4	4.0	4.0	1280.0	16.1	22.7	12.3 NO
400.	.9246E-04	4	3.0	3.0	960.0	18.9	29.6	15.6 NO
500.	.8346E-04	4	2.0	2.0	640.0	24.5	36.5	18.9 NO

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 100. M:

132. .1165E-03 3 5.0 5.0 1600.0 14.4 16.3 9.9 NO

DWASH= MEANS NO CALC MADE (CONC = 0.0)

DWASH=NO MEANS NO BUILDING DOWNWASH USED

DWASH=HS MEANS HUBER-SNYDER DOWNWASH USED

DWASH=SS MEANS SCHULMAN-SCIRE DOWNWASH USED

DWASH=NA MEANS DOWNWASH NOT APPLICABLE, X<3*LB

* SUMMARY OF TERRAIN HEIGHTS ENTERED FOR *
* SIMPLE ELEVATED TERRAIN PROCEDURE *

TERRAIN	DISTANCE RANGE (M)	
HT (M)	MINIMUM	MAXIMUM
0.	100.	500.

*** SUMMARY OF SCREEN MODEL RESULTS ***

CALCULATION	MAX CONC	DIST TO	TERRAIN
PROCEDURE	(UG/M**3)	MAX (M)	HT (M)
SIMPLE TERRAIN	.1165E-03	132.	0.

** REMEMBER TO INCLUDE BACKGROUND CONCENTRATIONS **

CALCULATION WORKSHEET

ORIGINATOR J P COLFER DATE 3/31/94 SHEET 1 OF 3
 CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED RC 04/20/94
 PROJECT MMR - SVE/AS TASK NO. 9750, K04.03.09
 SUBJECT CARCINOGENIC RISK FROM AIRBORNE EDB NEAR CADOX UNIT

ASSUMPTIONS & EXPOSURE FACTORS

- ① CONCENTRATION OF EDB IN AIR NEAR CADOX UNIT WAS CALCULATED BY THE SCREEN MODEL (SCREEN-1.1 MODEL DATED 88300) AND FOUND TO BE AT AN AVERAGE CONCENTRATION OF $1.165(\text{UD})^{-4} \frac{\mu\text{g}}{\text{M}^3}$ AT A DISTANCE OF 132 M FROM THE CADOX UNIT. THIS AVERAGE CONCENTRATION REPRESENTS THE AVERAGE CONCENTRATION DURING THE FIRST MONTH OF CADOX UNIT OPERATION.
- ② ASSUME NO DESTRUCTION/DEGRADATION OF EDB BY THE CADOX UNIT.
- ③ ASSUME THAT A HUMAN RECEPTOR RESIDES AT A LOCATION DOWNWIND OF THE CADOX UNIT AND BREATHES THE AIR CONTINUOUSLY DURING THE 4 MONTH REMEDIATION PHASE AT THE CONCENTRATION DESCRIBED IN STEP NO. 1.
- ④ RISK CALCULATION FORMULA (FROM RAGS, 1989)

$$\text{Risk} = \text{CDI} \times \text{SF}$$

CDI = CHRONIC DAILY INTAKE

SF = CANCER SLOPE FACTOR

- ⑤ FOR INHALATION OF AIRBORNE CHEMICALS (RAGS, 1989)

$$\text{INTAKE} = \frac{\text{CA} \times \text{IR} \times \text{ET} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}}$$

CA = CONTAMINANT AIR CONC. (mg/m^3)

IR = AIR INHALATION RATE (m^3/hr)

ET = EXPOSURE TIME (hr/d)

ED = EXPOSURE DURATION (yr)

BW = BODY WEIGHT (kg)

AT = AVERAGING TIME (d)



CALCULATION WORKSHEET

ORIGINATOR JP COLFER DATE 3/31/94 SHEET 2 OF 3
 CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED PC, 10/20/94
 PROJECT MMR- SVE-AS TASK NO. 9750.KD4.03.09
 SUBJECT CARCINOGENIC RISK FROM AIRBORNE EDB NEAR CADGX UNIT

⑤ cont'd EF = EXPOSURE FREQUENCY (d/yr)

⑥ ASSUMED EXPOSURE FACTORS:

$$CA = 1.165 \times 10^{-7} \text{ mg/m}^3 \quad \left(1.165 \times 10^{-4} \frac{\mu\text{g}}{\text{m}^3} \times \frac{\text{mg}}{10^3 \mu\text{g}} \right)$$

$$IR = 0.83 \text{ m}^3/\text{hr} \quad \left(\frac{20 \text{ m}^3}{\text{d}} \times \frac{\text{d}}{24 \text{ hr}} \right)$$

$$ET = 24 \text{ hr/d}$$

$$ED = 0.33 \text{ yr}$$

$$\left(4 \text{ mo} \times \frac{\text{yr}}{12 \text{ mo}} \right)$$

$$EF = 365 \text{ d/yr}$$

$$BW = 70 \text{ kg}$$

$$AT = 25,550 \text{ d}$$

$$(365 \text{ d/yr} \times 70 \text{ yr})$$

⑦ INTAKE:

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3/31/94

$$\frac{1.165 (10)^{-7} \frac{\text{mg}}{\text{m}^3} \times 0.83 \frac{\text{m}^3}{\text{hr}} \times \frac{24 \text{ hr}}{\text{d}} \times \frac{365 \text{ d}}{\text{yr}} \times 0.33 \text{ yr}}{70 \text{ kg} \times 25,550 \text{ d}} = 1.56 (10)^{-10} \frac{\text{mg}}{\text{kg d}}$$

⑧ EDB SLOPE FACTOR FOR AIR:

$$2.2 (10)^{-4} \frac{\text{m}^3}{\mu\text{g}} = \text{UNIT RISK FOR AIR (MMR RA HANDBOOK)}$$

$$3.5 (10)^3 \frac{\mu\text{g kg d}}{\text{mg m}^3} = \text{CONVERSION FACTOR TO OBTAIN CSF}$$

$$\text{CSF} = 2.2 (10)^{-4} \frac{\text{m}^3}{\mu\text{g}} \times 3.5 (10)^3 \frac{\mu\text{g kg d}}{\text{mg m}^3} = 0.77 \frac{\text{kg d}}{\text{mg}}$$

JPC
3/31/94



CALCULATION WORKSHEET

ORIGINATOR JP COLFER DATE 3/31/94 SHEET 3 OF 3
CALC. NO. _____ REV. NO. 0 DATE _____ CHECKED RC 04/26/94
PROJECT MMR - SVE - AS TASK NO. 9750.K04.03.09
SUBJECT CARCINOGENIC RISK FROM AIRBORNE EDB NEAR CADOX UNIT

⑨ RISK:

$$\begin{aligned} \text{Risk} &= \text{CDI} \times \text{SF} \\ &= 1.56 (10)^{-10} \frac{\text{mg}}{\text{kg d}} \times 0.77 \frac{\text{kg d}}{\text{mg}} = 1.2 (10)^{-10} \end{aligned}$$

JPC
3/31/94

⑩ CONCLUSION:

THE RISK FOR CONTINUOUS INHALATION OF THE EDB STRIPPED FROM GROUNDWATER DURING THE SPARGING OPERATION IS CALCULATED TO BE 1.2×10^{-10} . THIS NUMBER IS WELL BELOW THE EPA CLEAN UP GUIDELINES OF $10^{-4} - 10^{-6}$. THE CALCULATION FOR EDB CONCENTRATION IN AIR WAS CONSERVATIVE AS WAS THE SELECTION OF THE RECEPTOR AND THE EXPOSURE FACTORS. IN CONCLUSION, NO APPRECIABLE HUMAN CARCINOGENIC RISK IS EXPECTED FOR AREA RESIDENTS DUE TO OPERATION OF THE GROUNDWATER AIR SPARGING/CADOX SYSTEM.

JPColfer
3/31/94



SECTION 10

Protective Piping at Road Crossings

CALCULATION WORKSHEET

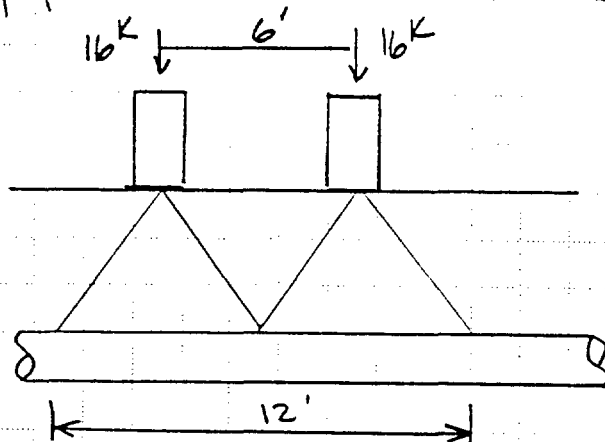
ORIGINATOR R.E. HOEKSTRA DATE 3-1-94 SHEET 1 OF 2
CALC. NO. _____ REV. NO. _____ DATE 5/31/94 CHECKED J. HAWK
PROJECT MMP SVE / AS TASK NO. 9750-K04.03.09
SUBJECT GUARD Pipe DESIGN

GUARD Pipe DESIGN.

Purpose: THE GUARD Pipe will be a STEEL pipe THAT WILL PROTECT THE PVC piping from TRUCK LOADINGS

LOADING - Assume a HS 20-44 w/ 32,000 # per AXLE.

The pipe will be three feet below grade.



$$\text{TOTAL MAXIMUM LOADING} = \frac{32,000}{12} = 2.67 \text{ K/ft.}$$

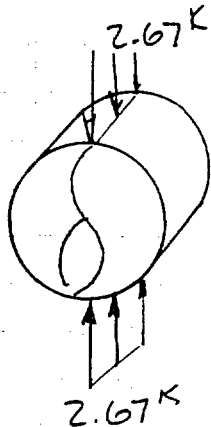
CHECK THE 8" ϕ Pipe - WORSE CASE



CALCULATION WORKSHEET

ORIGINATOR RE HOOEKSTRA DATE 3-1-94 SHEET 2 OF 2
 CALC. NO. _____ REV. NO. 0 DATE 5/31/94 CHECKED J. H. W. K.
 PROJECT MMR SUE/AS TASK NO. 9750-K04.03.09
 SUBJECT GUARD Pipe Design

CHECK THE 8" schedule 40 pipe



$$M_{max}^+ = 0.3183 W R K_2^*$$

$$M_{max}^- = - (0.5 - 0.3183 K_2) W R^*$$

$$R = 4.15''$$

$$W = 2.67 K$$

$$K_2 = 1 - \alpha$$

* ROARK'S FORMULA
for STRESS &
STRAIN

$$\alpha = I / A R^2$$

$$I = 72.5$$

$$A = 8.40$$

$$\alpha = 72.5 / 8.4 * 4.15^2$$

$$\alpha = 0.5011$$

$$M_{max}^+ = 0.3183 (2.67) (4.15) (0.4989)$$

$$= 1.75 K''$$

$$M_{max}^- = - (0.5 - 0.3183 * 0.4989) 2.67 (4.15)$$

$$= 3.54 K''$$

$$S = \frac{I}{c} = \frac{72.5}{6} = 12.083$$

$$\sigma = \frac{M}{S} = \frac{3.54 K''}{12.083} = 0.292 K''$$

8" ϕ Pipe OK.

$$\sigma_{in pipe} = \frac{3.54 K''}{.2074} = 17.07 < .66 F_y = 27 Ksi$$



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SECTION 11

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